PHD

Estimating the Cost of Engineering Services using Parametrics and the Bathtub Failure Model

Huang, Xiaoxi

Award date:
2012

Awarding institution:
University of Bath

Estimating the cost of engineering services using parametrics and the bathtub failure model

Xiaoxi Huang

A thesis submitted for the degree of Doctor of Philosophy
University of Bath
Department of Mechanical Engineering
April 2012

Contents

ACKNOWLEDGEMENTS

Foremost, I would like to thanks Dr. Linda Newnes, Dr. Glenn Parry and Prof. Antony R. Mileham for a great deal of guidance and support during the research.

I would also like to thank the Engineering and Physical Sciences Research Council (EPSRC) for providing funding for this research, as well as all the colleagues I have worked with who have shared their knowledge and research experience with me.

I wish to thank the industrial company for providing valuable data and useful resources during the research. I also wish to thank all the members in the Financial and After-sales Service Departments, especially Manager Hu and Manager Yang for their support and guidance.

Finally, a special gratitude should be expressed to my parents, relatives, Dr. Yu Qiu and other friends for supporting my PhD study and helping me go through this challenging and interesting journey.

ABSTRACT

In the engineering domain, customers traditionally purchase a product by paying a one-off price to the supplier. Currently, customers are increasingly demanding engineering services in different disciplines, such as in the aerospace, defence, manufacturing and construction sectors. This means that the customer may buy a product, which includes an integrated service or purchase the usage of a product/service (i.e. availability and capability) rather than the ownership of a product. To meet this demand for engineering services rather than stand-alone products, many companies have moved from providing a tangible product to offering such services.

In both academia and industry, the majority of the activities have focused on estimating the cost for products with little in the area of estimating the cost of providing engineering services. There appears to be a clear knowledge gap in the field of costing models and rules for providing such services. It is this gap in knowledge, which is the focus of the research presented in this thesis.

This research is focused on estimating the cost for engineering services using parametrics and the bathtub failure model. This is illustrated through the application to a Chinese manufacturing and service provider. Eight years of cost-related data such as historical bills, service charges, maintenance records, and costs for storage has been collected. Observations, questionnaires and structured meetings have been conducted within the company. A methodology and a cost model for estimating the cost for engineering services are provided.

The major contribution of this research is the creation of an approach, which is to estimate the cost of engineering services using parametrics and the bathtub failure model.

LIST OF PUBLICATIONS

1. Huang, X. X., Newnes, L. B. and Parry, G. C. (2012). The adaptation of product cost estimation techniques to estimate the cost of service. *International Journal of Computer Integrated Manufacturing*, **25**(4-5): 417-431.

2. Huang, X.X., Newnes, L.B. and Parry, G.C. (2011). An analysis of industrial practice for estimating the in-service costs of a product service system. *Proceedings of the ASME 2011 International Design Engineering Technical Conference & Computers and information in engineering Conference*. August 28-31, 2011, Washington, DC, USA.

3. Huang, X., Newnes, L. and Parry, G. (2010). A framework for development of models and analysis of the provision of through-life-costing for an engineering service. In: *Grand Challenge in Service*, 21st September 2010, Cambridge UK.

4. Huang, X.X., Newnes, L.B. and Parry, G.C. (2009). A critique of product and service based systems. In: Ceglarek, D., ed. *Advances in Manufacturing Technology - XXIII: Proceedings of the 7th International Conference on Manufacturing Research (ICMR2009)*, Nottingham: Salient Books. pp.: 405-412.

5. Huang, X.X., Kreye, M., Parry, G.C. , Goh, Y.M. and Newnes, L.B. (2012). The cost of service. In Sandborn P. *Cost Analysis of Electronic Systems*. *– at press*

6. Parry, G.C., Newnes, L.B. and Huang, X.X., (2011). Goods, Products and Services in Macintyre, M., Parry, G.C. and Angelis J. (Eds.) *Service Design and Delivery*. New York; London: Springer.

7. Parry, G.C., Newnes, L.B. and Huang, X.X. February (2009). Products and Services: similarities and differences. – Report presented to BAE Systems as a contribution towards the joint EPSRC/BAE funded S4T programme -*not in public domain*

8. Parry, G.C., Newnes, L.B. and Huang, X.X. July (2009). Products and Services: management. – Report presented to BAE Systems as a contribution towards the joint EPSRC/BAE funded S4T programme - *not in public domain*

LIST OF ABBRECIATION

ABC: Activity-based Cost

BPNN: Back Propagation Neural Network

CBR: Case-based Reasoning

CER: Cost Estimating Relationship

CERs: Cost Estimating Relationships

DSS: Decision Support Systems

ESCE: Engineering Service Cost Estimation

PCE: Product Cost Estimating

PSS: Product Service System

WBS: Work Breakdown Structure

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

The aim of the research presented in this dissertation was to estimate the cost of engineering services using parametrics and the bathtub failure model. This chapter describes the context of the research, with an emphasis on the industrial need for engineering services. The important role of engineering services, different types of engineering services, the definition of engineering services and the challenges of providing such services are discussed. The overall aim and objectives of the research are then presented, followed by an outline of the thesis.

1.1 Move from Products to Engineering Services

In the engineering domain, customers traditionally purchase a product by paying a one-off price to the supplier (Huang, 2009; 2012). Customers are increasingly demanding service-added products or engineering services in various sectors, such as aerospace, defence, manufacturing and construction (Davies, 2003; Brax, 2005). This means that the customer may buy a product, which includes an integrated service or purchase the usage of a product/service (i.e. availability and capability) rather than the ownership of a product (Gray, 2009). To meet this demand for services rather than stand-alone products, many companies have moved from providing a tangible product to offering engineering services (Neely, 2007; Ward & Graves, 2007).

1.2 Why Engineering Services are important

Traditional product-oriented companies such as BAE Systems, Rolls Royce, and ABB have been gradually moving towards engineering services (Datta & Roy, 2010). For example, Rolls Royce won an engineering service contract worth \$1.8

billion, at list prices, for Trent engines to power twenty new aircraft for Air China in 2010 (Rolls-Royce, 2010). The contract includes long-term Total Care® service support and aircraft deliveries. In this particular example, Air China, do not buy the engines but pay for an engineering service – in this case an engine, which is available for use. The revenue from such engineering services has become a key area for long-term profit generation within some companies. Rolls-Royce 2009 accounts show estimates of engine sales for defence at $170billion, with an after-sales service market being worth $280billion (Royce-Rolls, 2009).

Apart from the financial benefit, which may be achieved, there are also potential advantages through improved interactions and bonding with customers (Brax, 2005). The provision of such services can also be used to assist the sale of physical products, create potential opportunities in matured markets and minimize the effect of cash flow during different stages of an economic cycle of a product (Davies, 2003; Xu et al., 2006). Hence, to be able to offer practical and reliable engineering services is becoming considerably important for these companies.

1.3 What are the different types of engineering services

Different companies may offer different types of engineering services, hence such services can be separated into four different categories as depicted in Table 1.1 (Baines et al., 2011); namely

a) Basic engineering services such as spare parts for cars. Here companies such as Melbourne Autos (2012) that delivers spare parts for a diverse range of cars for both foreign and the UK customers.

b) Product and product oriented services. In this type of services the company provides products and supporting services such as repair, maintenance and support of the products. Examples include Rolls-Royce where they still sell the engines, as well as offering services of the engine for example via TotalCare® (Rolls-Royce, 2011).

c) Providing service provision of existing platforms. In this case the service company focuses on providing support for products already purchased by customers. For example BAE Systems Maritime Services focus on providing through life support, i.e. availability and readiness of the fleet to customers (BAE Systems, 2012).

d) Typical companies in this type of services utilise the products provided by the spare parts services (Type a) and then provide maintenance and support services such as those provided by Land Rover franchise, e.g. Guy Salmon (2012).

Table 1.1 Four types of engineering services offered by different companies

(adapted from Baines et al., 2011)

Different types of companies	Conventional manufacturers	Combined original equipment manufacture and product-centric services	Exclusive focused on product-centric services	Conventional service providers
Different types of engineering services	a) Companies focus on offering basic engineering services.	b) Companies focus on offering products and product-oriented services.	c) Companies focus entirely on servicing their existing installed platforms.	d) Companies focus entirely on services without actually manufacturing the products.
Examples	• Melbourne Autos	• Rolls-Royce	• BAE Systems - Maritime services	• Franchised distributor of Land Rover - Guy Salmon

1.4 Definition of Engineering Services

The engineering services that the researcher investigated in this thesis are within service type b), provided by companies that focus on offering both products and product-oriented services (Table 1.1). An industrial case study company is selected as the basis for this research. Although companies, such as Rolls-Royce and BAE Systems might provide more complex engineering services than the case study company, the premise is that they are still engineering services and that whether the engineering service is simple or complex, the need to estimate the cost in an effective manner is still important.

In this thesis, engineering services are defined as those offered by machine service support, such as phone services, spare parts services and on-site repair services to customers who purchased the machines from the service provider. This definition of engineering services is used consistently throughout the thesis.

1.5 Challenges of providing engineering services

In order to provide engineering services, there is a need for companies to understand the costs of providing such services (operations and support). This is one of the key challenges for industry. Currently, in the defence sector estimating the through-life cost of military provision, in particular for the engineering service costs of such equipment, which can account for up to 75% of the total expenditure through the products life, is a major challenge (Mathaisel et al., 2009). To meet this challenge and manage the acquisition of capability the Ministry of Defence (MoD) has moved to contracting for availability (a subset of capability), i.e. the contractor has to provide engineering services (Gray, 2009). However, a review of the domain has found that very few cost estimating tools model the cost for engineering services (Cheung et al., 2009a). For example the cost associated with allocating service staff to customers' site based on the number of military equipment in-operation would help the service provider to allocate their staff to provide more economic and efficient engineering services. Providers of engineering services such as those supporting machinery have the same challenges.

The challenge of estimating the costs of engineering services is also found in infrastructure activities. Patel (2011) found that in Tanzania where companies had moved from offering road builds and then being paid to maintain the road on a cost plus basis moved to providing the product and then a fixed fee for maintaining roads, they underestimated the cost of the in-operation support by 50%. The contract was a long-term contract and they could not change the price of the service they were providing. However, if the company in Tanzania understood how to price for such engineering services i.e. for maintaining roads based on different contract lengths, it would help the company reduce losses and gain more profits in the long term. In other words they could determine, based on different contract lengths, the cost of the in-operation support. Hence, it is important for these companies to understand how to estimate the cost for providing engineering services, in particular how to price an engineering service contract realistically and reliably based on different contract lengths and how to allocate service staff based on the number of machines in-operation.

Furthermore, in both academia and industry, the majority of extent literature focuses on estimating the cost for products with little in the area of estimating the cost of providing engineering services (Scanlan et al., 2006; Newnes et al., 2007; Castagne et al., 2008; Cheung et al., 2009a). For instance, there are a large number of techniques and methodologies, which have been specifically designed to estimate the costs of a product in different circumstances (Roy and Kerr, 2003; Niazi et al., 2006). Moreover, a diverse selection of costing software, such as True Planning (PRICE, 2011) and the SEER modules (SEER, 2009) have been designed with a product-oriented focus. Although product-focused methods and tools may be adapted to estimate the costs of providing engineering services (Chapter 2), it is important to consider the interaction between products and engineering services. In the research presented in this thesis the parametric cost estimating technique is selected to model the cost for engineering services, this is explained in detail in Chapter 2.

There appears to be a clear knowledge gap in this particular field, especially in the provision of costing models and rules for providing engineering services. It is this gap in knowledge, which is the focus of the research presented in this thesis. From a review of the literature and an analysis of industrial practice, this PhD research has identified this gap and ascertained that to estimate the cost of providing engineering services the most appropriate approach is the use of parametrics and the bathtub failure model. The outcomes from this research are then evaluated and analysed through an industrial case study.

1.6 Overview of Research

To fulfil the gap, the overall aim of this research was to estimate the cost of engineering services using parametrics and the bathtub failure model.

To meet the aim of the research, the following specific objectives were defined.

1) Select an industrial case study, collect and analyse historical data from the case study company.
2) Create an engineering services cost model for the case study company.
3) Validate the engineering services cost model.
4) Test service scenarios and propose service solutions with associated costing.

1.7 Outline of Research

The thesis is split into ten chapters as shown in Figure 1.1.

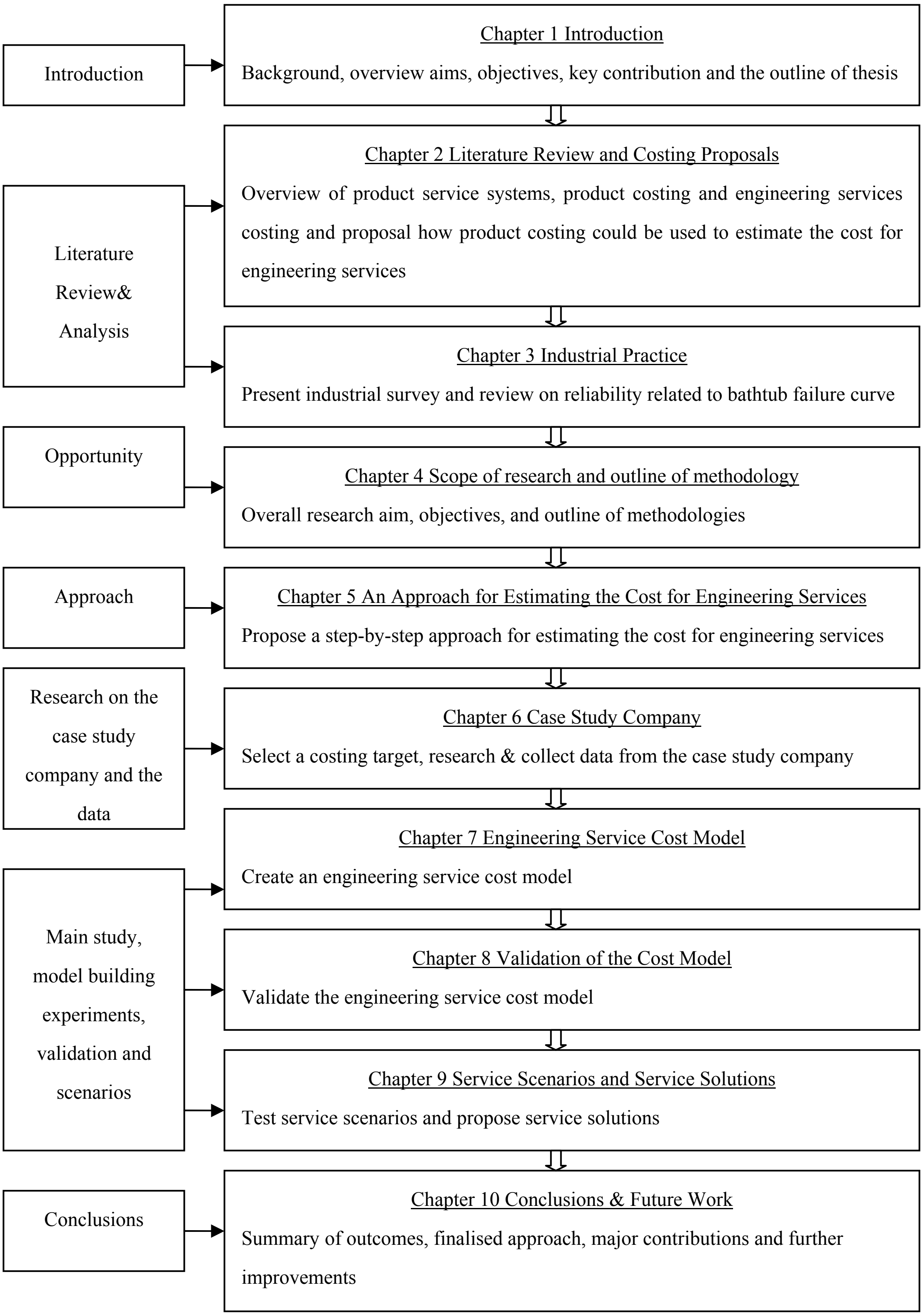

Figure 1.1 Structure of Research and Layout of Thesis

Chapter 2 Review of Literature and Costing Proposals

The focus of this review was to identify gaps in the field of engineering services costing and to review the approaches of costing techniques for this research. To this end, a top-level review on Product Service System (PSS) and trends in industry today are presented, and engineering services belonging to a particular type of PSS are identified in Section 2.1. A broad range of viewpoints on product costing and engineering services costing are presented in Section 2.2, in particular, identifying the gaps in the field of engineering services costing. Section 2.3 is focused on how product costing techniques could be adapted to estimate the cost for engineering services. More importantly, parametrics is adapted for this researched with justified reasons in Section 2.4. Section 2.5 then explores the literature in product and PSS costing tools and identifies a gap in engineering service costing tools.

2.1 Product Service Systems

Baines et al (2007) states that PSS is "*an integrated product and service offering that delivers value in use*." This system coincides with a recent trend in business strategy, which is to offer solutions instead of stand-alone products or services to customers (Galbraith, 2002). Some of the worlds leading companies, such as IBM, General Electric and Rolls-Royce now compete by providing integrated solutions as opposed to pure product offerings. Rolls-Royce for example, offer the "Total Care®" scheme (Rolls-Royce, 2011) to various airlines, which provide maintenance, overhaul and upgrade services through the products' lifespan in addition to the selling of jet engines (Davies et al., 2006).

Traditionally, there are three types of PSSs which are product oriented PSS, use oriented PSS and result oriented PSS (Meier et al., 2010). Product oriented PSSs focus on products with additional services provided. Usually customer retains the ownership of the tangible product. For example, the installation and implementation services directly provided by manufacturers is an example of the product oriented PSSs. In contrast, use oriented PSSs shift from selling pure products to providing product functions via services. The ownership of the tangible product is transferred from the customer to the service provider. In this case, the service provider offers services through distribution and payment systems, e.g. car leasing and sharing (Cook et al., 2006). A different approach compared with both product oriented and use oriented PSSs is the result oriented PSSs which provides services instead of products (Yang et al, 2010). An example would be laundry services where the service itself replaces the need for customers to own their personal washing machines.

Neely (2008) extend the traditional categories of PSSs by adding service oriented PSS and integration oriented PSS. Comparing with traditional PSSs, service oriented PSS integrates services into products rather than product plus service. Health usage monitoring systems and intelligence vehicle health management are classic examples.

On the other hand, integration oriented PSS is essentially products plus services. Although the ownership of the tangible product belongs to the customer, the principle of this type is to provide additional services through vertical integration. For example, IBM Company not only designs and manufactures computers, but also provide delivery, training, and after-sales services to their customers.

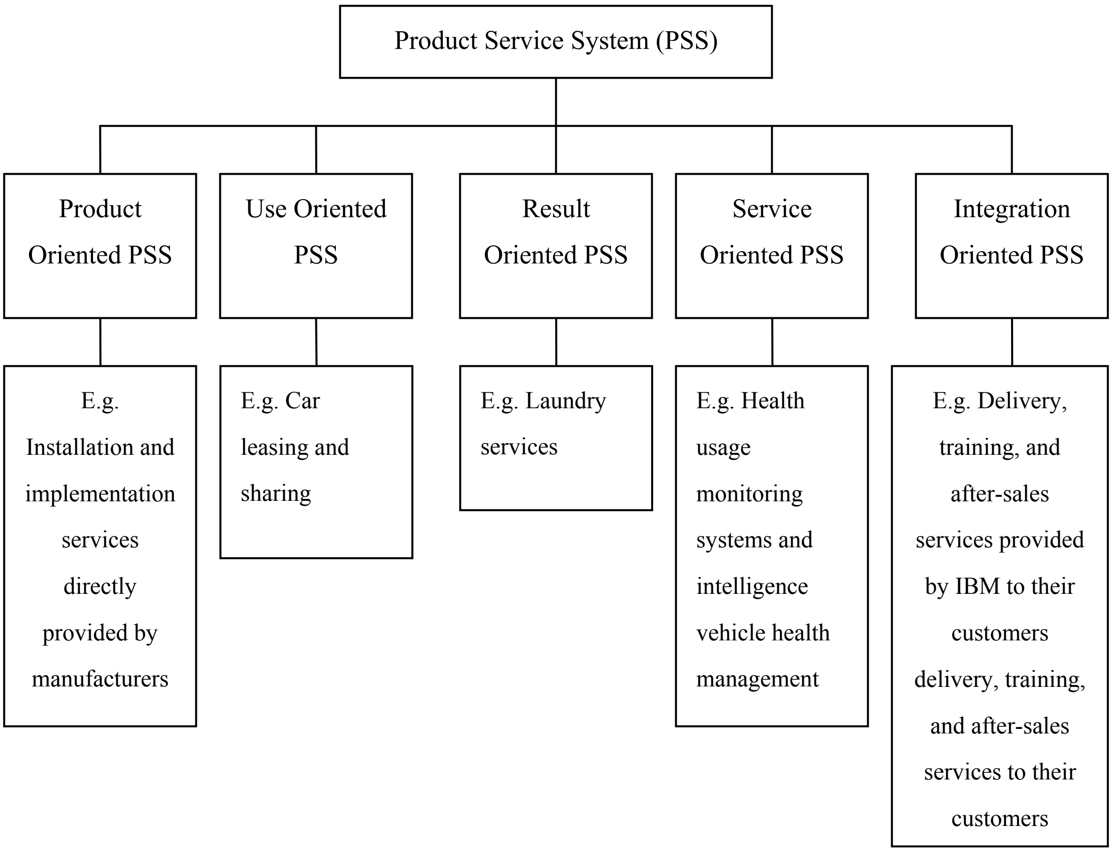

Figure 2.1 A spectrum of types of product-service offerings (Adapted from Neely, 2008)

Based on existing literature, the author has modified and expanded the spectrum of types of product-service offerings as depicted in Figure 2.1. In this thesis, engineering services are defined as companies that offered machine service support, including phone services, spare parts services and on-site repair service to customers who purchased the machines from the service provider. This means that customers have the ownership of the machine, whereas machine service provider is responsible for selling the machine as well as providing a range of machine-related services to customer. By comparing the engineering services with the spectrum of types of product-service offerings as shown in Figure 2.1, it is found that the engineering services described in this thesis is a particular type of PSS, which is the integration oriented PSS. Although companies, such as IBM Company, Rolls-Royce and BAE

Systems might provide more complex engineering services than the engineering services described in this thesis, the approach for estimating the cost for providing such services could provide directions and guidance for these companies. Hence, engineering services take an important role of PSS. More importantly, by understanding how to estimate the cost for providing engineering services will assist the cost estimators to predict the cost of offering integration oriented PSS efficiently and effectively.

In the next section, it presents a review on product costing and engineering service costing, including definitions and costing techniques. More importantly, gaps in the field of engineering service costing are identified.

2.2 Review of Cost Estimating Approaches

The Association for the Advancement of Cost Engineering (CET, 2010), states that cost estimation aims to determine the quantity and predict the costs of constructing a facility, manufacturing goods, or delivering a service. Product cost estimation is often involved in estimating the cost of producing and selling a physical good, such as a car, which includes the costs of research and development, designing, manufacturing, marketing and distribution, and customer service (Park *et al.* 2002). In comparison, engineering service cost estimation commonly deals with the in-service phase of a product service system, such as maintenance and repair of machines and training of staff (Castagne et al., 2008; Lee et al., 2008).

The following section presents a summary of the definition of product and engineering service cost estimation, which is used within this research to critique the literature.

2.2.1 Product Costing

Since, the twentieth century, research in the field of product cost estimation has been undertaken (Clark, 1985; Ostwald, 1991; Blocher *et al.*, 2005). Examples include cost estimation of standard or customised components, general or specific cost optimisation techniques, and estimation techniques applied at the different life cycle phases (Niazi *et al.*, 2006). In addition, PCE techniques have been categorised using certain classifications by numerous researchers, e.g. Niazi et al. (2006), and Asiedu and Gu (1998). The latter classify PCE approaches into parametric, analogous, and detailed methods and later, Ben-Arieh and Qian (2003) extended the scope of PCE techniques into intuitive, analogical, parametric, and analytical based. Similarly, Shehab and Abdalla (2001) categorises PCE methods into intuitive, parametric, variant-based, and generative without defining them clearly. They later develop the PCE methods used at the design stage into knowledge-, feature-, function-, and operations-based approaches. In contrast, a different way to classify PCE techniques is to separate them into cost estimation of traditional detailed-breakdown, simplified-breakdown, group-technology-based, regression-based, and activity-based (Zhang *et al.*, 1996).

Although there are many different ways to classify PCE approaches, a comprehensive hierarchical classification of the estimation techniques was not fully developed until 2006 (Niazi *et al.*, 2006). Niazi and his colleagues categorised the PCE techniques into qualitative and quantitative.

The fundamental idea of qualitative cost estimation techniques is to identify whether a new product has any similarities with previous products. The identified similarities are then used to help build the cost estimate for the new product based on similar features, attributes etc. This greatly reduces the time and effort compared with estimating the cost from scratch. The key requirements of implementing these types of techniques successfully are historical design and manufacturing data, and/or previous cost estimating experts' experience. Qualitative cost estimation techniques can be further categorised into intuitive and analogical techniques, which will be discussed in, detail elsewhere.

However, rather than relying on the past data or an estimator's knowledge, focusing on a detailed analysis of a product design, its features and the corresponding manufacturing processes are the major characteristics of quantitative cost estimation techniques (Roy *et al.*, 2001). By applying these types of techniques, costs are usually estimated by using mathematical formula, taking different product or resources parameters during a whole product life cycle into account. This approach would generally obtain more accurate costing results than the qualitative method (Niazi *et al.*, 2006); however, the qualitative approaches often enable the user to obtain rough order of magnitude cost estimates during the early conceptual design stage of a product.

Hence, qualitative techniques are more appropriate to implement when the estimating time is limited, past data or experts' knowledge is available, and the estimating accuracy requirement is moderate (Roy *et al.*, 2001). In contrast, quantitative techniques are preferable when the estimating time is sufficient, relationships of different cost variables are identified, and the estimating accuracy requirement is comparably high. Quantitative cost estimation techniques can be further categorised into parametric and analytical techniques, which will be discussed in, detail elsewhere (Niazi *et al.*, 2006).

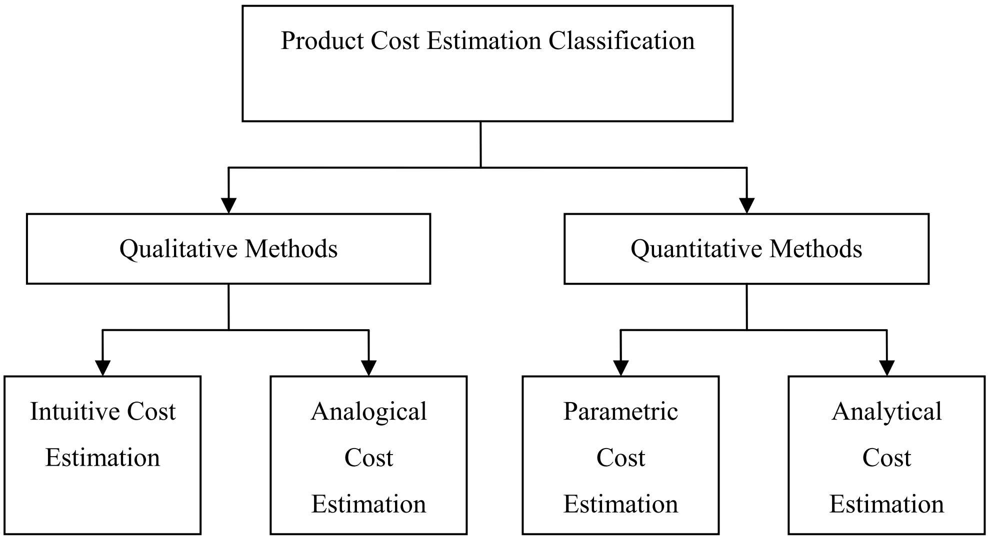

Figure 2.2 Classification of PCE techniques (adapted from Niazi et al., 2006).

Cost estimation techniques are often summarised and illustrated as a tree diagram as shown in Figure 2.2 (Niazi *et al.*, 2006). The qualitative and quantitative techniques presented in Figure 3.1 are the core techniques utilised by many researchers and industry (Ben-Arieh and Qian, 2003; Goh et al., 2010; Huang et al., 2012). As these are the most common PCE techniques they are used as the basis of analysis within this chapter. The bottom row of Figure 2.2 illustrates how each technique can be sectioned into more specific systems or cost models, which will be discussed in detail in the following sections.

2.2.2 Engineering Service Costing

Throughout the review of cost estimating approaches, there were minimal findings in terms of engineering service cost estimation (ESCE). The concept of delivering an engineering service has been researched since the twentieth century and widely applied in numerous sectors such as aerospace, information technology (IT), health care, finance, civil construction, and defence areas (Jian and Hong-fu, 2004; Ward and Graves, 2007; Tan *et al.*, 2009). The delivery of engineering services can, for example, include maintenance and repair of machines, and training of staff. The cost estimation of maintenance is one of the few ESCE areas, which have been researched, especially in the aerospace industry (Wallace, et al., 2000; Castagne et al., 2008). In military warfare the operational costs are uncertain, such as the weather of the operation, the experience of the operator, and the failure of the airplane. Hence, Deng (1982, 1989) developed the grey model, which incorporated uncertainties and is used for forecasting airplane maintenance costs. The maintenance costs are estimated by comparing the target case with similar cases in the past. To extent Deng's research, Azzeh and his colleagues (2010) improved the model by reducing uncertainties and improving the estimates credibility.

In addition, other ESCE areas have also been investigated within the aerospace domain including contracts for spares or preventative maintenance, fixed price repairs, component management and stock exchanges (Ward and Graves, 2007).

Based on the existing literature review, there are gaps within ESCE and it should be exploited in areas other than aerospace. There is also limited literature relating to ESCE, although there is some research on maintenance and contracting (Datta and Roy, 2010; Bowman and Schmee, 2001). For example, Lanza and Ruhl (2009) develop an approach by adapting the Monte Carlo method to estimate the costs of providing maintenance service for a four year contract. The model focuses on corrective maintenance service, which is an important part of the engineering service. However, some other engineering services, such as preventative maintenance service, phone service, training service are not included. Similarly, Silva and his colleagues (2008) develop a methodology, which is used to calculate the costs of providing maintenance service for a food-product plant. Although there are methodologies and tools for estimating the costs of maintenance, there is still a gap in estimating the costs of an engineering service.

To ascertain the way forward in modelling engineering service costs the following sections present various PCE techniques and the author's views on how these methods can be applied to engineering services. This analysis then leads to presenting how these PCE techniques can be used to estimate the cost of engineering services.

2.3 Applying PCE to Engineering Service Cost Estimating

This section provides a detailed analysis of PCE techniques and presents through a critique, how they could be applied to ESCE. Each section is presented as follows. The PCE technique is described in relation to the current literature. The author of this PhD dissertation then presents her view on how the technique could be used for ESCE.

2.3.1 Intuitive Cost Estimation Techniques

The intuitive cost estimation techniques are primarily dependent on past experience i.e. a cost estimator's expert knowledge is the key to their success. Their experience can be applied either directly or through some forms of storage of this knowledge, such as rules, decision trees and judgements, to generate cost estimates for components and assemblies (Williams, 1992; Niazi *et al.*, 2006; Cheung et al., 2009b). Table 2.1 summarises the intuitive cost estimation techniques which can be categorised into case-based systems and decision support systems, each having advantages and drawbacks which are now analysed.

Table 2.1 Intuitive cost estimation methods used on products (adapted from Niazi et al., 2006)

Product Cost Estimation (PCE) Methods			Main Advantages	Main Disadvantages
Intuitive Cost Estimation Method	Case-Based Systems		Design approach tends to be more creative	Mainly rely on past data and previous experience
	Decision Support Systems	Rule-based systems	Capable of providing optimised results	It is often time-consuming
		Fuzzy logic systems	Considering uncertainty to produce a reliable estimate	Cost estimate complex features is often time-consuming
		Expert systems	Able to estimate costs more efficiently, reliable and accurately	It involves complicated programming

a. Case-based Reasoning

Case-based systems are also known as cased-based reasoning (CBR). This approach is designed to estimate the cost of a product by assuming that similar products have similar costs (Banga, 2010; Jiang et al., 2010; Xia et al., 2010). Figure 2.3 illustrates the overview of the CBR process (Aamodt and Plaza, 1994). The approach used in CBR starts by identification of the problems for the new case. The new component or product's design specifications are defined and the cost estimate is based on the closest design match from the knowledge base of previous cases. The process then incorporates modifications either by retrieving similar attributes from the design database or by designing new ones altogether. The adapted solution of a new design then conforms to the outlined design specification when all the necessary changes are adapted in a similar way. This solution can either be a quick cost estimation result or be ready to verify for a more accurate and detailed cost estimation. If it is the latter, the new design solution will be stored in the knowledge base and tested to provide a final design solution and the associated cost estimate. One of the major drawbacks of this technique is that it is heavily dependent on past data and models although it often generates an innovative design. Therefore, applying this approach to products, which have limited historical information or relevant cost data may not be possible.

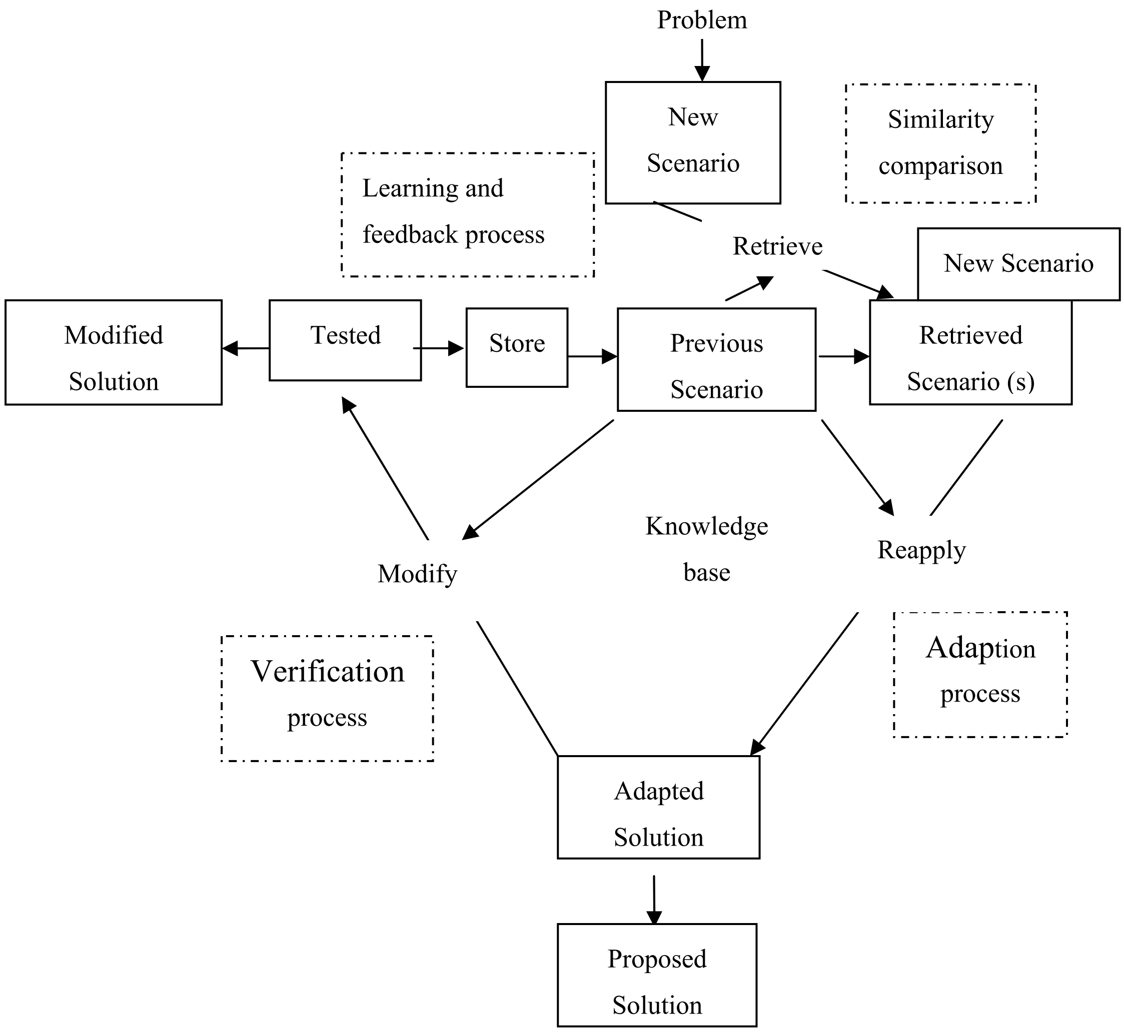

Figure 2.3 Case-based reasoning process (adapted from Aamodt and Plaza, 1994).

<u>*a) How CBR could be used for ESCE:*</u>

By applying the same concept, this approach could also estimate the cost of an engineering service by assuming that similar engineering services have similar costs. For example, if a company estimates leasing a car to person A costs X on one occasion, it is likely on the next occurrence that the company estimates a similar amount for leasing the same car to person B, providing the service condition are the same. However, in reality, comparing new engineering service conditions to previous occurrences could be more complex than comparing new products to previous products. This is because engineering services may have intangible attributes as well as tangible ones, necessary to make the comparison. For example, the manner and the appearance of maintenance staff might affect the overall service quality that customers perceive. Also service delivery is usually a dynamic and flexible process, which makes it more complex and time-consuming to build up the knowledge data base.

Using the example of estimating the cost for the car leasing business, not only are attributes related to the car, such as its age, maintenance record, mileage considered, but more importantly, attributes related to, for example, the driver's driving experience, temper, driving history and the weather, may also require consideration. Therefore, one of the greatest challenges for applying CBR to engineering services is to understand how to identify and estimate differences and similarities between new services and existing services.

Moreover, as engineering services is a type of PSSs, it might have the characteristics of both product and service. Therefore, when the CBR approach is applied to estimate the cost of engineering services it should generate a knowledge data base, which is applicable for such services. This may result in a delivery process, which is highly dynamic and flexible.

b. Decision Support Systems (DSS)

The main purpose of Decision support systems (DSS) within cost estimation are that they are used to help a cost estimator to select the most appropriate design solution by utilising information from the knowledge database (Omar et al., 2009). Figure 2.4 shows the processes of implementing a DSS approach in PCE.

In this case a car example is provided to illustrate the concept of the DSS process. If someone wants to purchase a car, they could select their own specification from the seller by selecting the model type, the colour for the main body, the wheel and seat types etc. Then the car manufacturer would design a product specification based on the customer's requirement. Based on this specification, the manufacturer would select the most appropriate design methodology and production process to build this car. After deciding these, an estimated cost for manufacturing this car is generated. Other costs, such as marketing costs, sales costs, and some pre-determined profit margin are added on top of the production costs to offer a price for the customer. If the customer is dissatisfied with the offer, they could either reject the offer or negotiate with the dealer. If the customer accepts the offer, a deposit is paid and an order for manufacturing and delivering the car has been executed.

Table 2.1 (Niazi et al., 2006) depicts how decision support techniques can be separated into rule-based systems, fuzzy logic systems and expert systems，which will be discussed in detail in the next section.

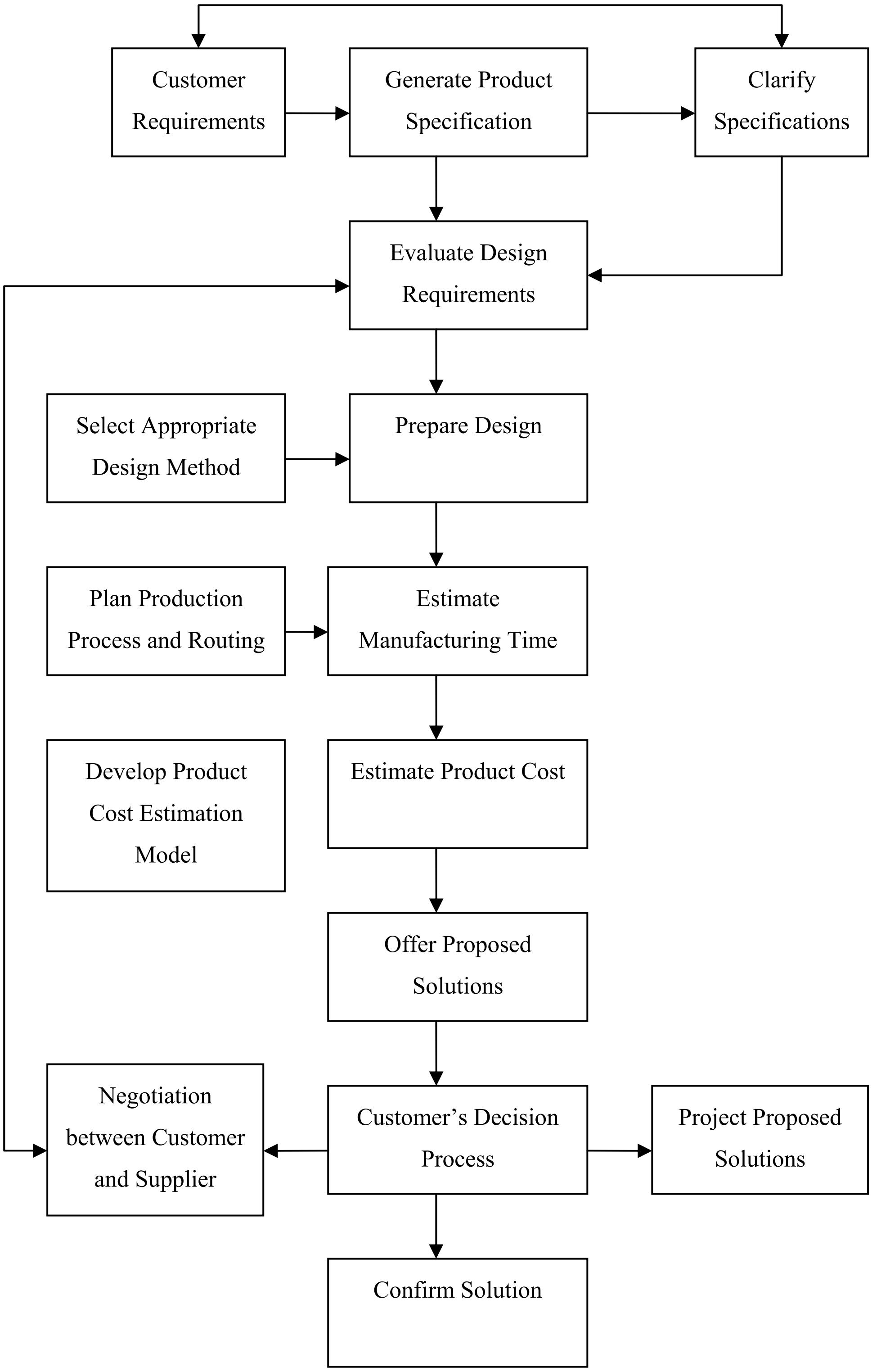

Figure 2.4 Decision support system approach to product cost estimation (adapted from Niazi et al.,2006)

b1. Rule-based Systems

The core idea of this approach is to establish a set of design and/or manufacturing constraints to help manufacturers to select the more appropriate manufacturing processes in order to calculate the product cost. Gayretli and Abdalla (1999) develop a rule in the form 'If premises Then conclusion' to help select a certain type of production process to estimate process time and cost based on parts features. This means that a product can be separated into different components and features, with each being through a similar process to calculate the cost. Then the total cost of a product can be generated as a sum of the costs of different parts. The advantage of this technique is that it is capable of providing optimised solutions by adopting the most appropriate product processes; however, the limitation of this approach is that it is time-consuming as a product could have countless parts and features to be evaluated.

b1. How Rule-based Systems could be used for ESCE:

In comparison, the rule-based system is likely to apply in engineering services with the aid of further research on a rule-based algorithm or standard for a product service offering. The challenge could be how to develop a comprehensive rule-based system, which can carry out multiple tasks based on the characteristics of both goods and services.

In order to apply this technique, a rule in the form 'If premises Then conclusion' should be designed based on the characteristics of both products and services. For instance, the task is to deliver flowers to a customer at a required time. If the time to reach the customer's place can be estimated in advance, the delivery person and transport are made available within working hours then the cost for this service can be estimated by adding up the costs of labour, fuel and flowers. However, this estimation is probably not accurate in reality, as it neglects the important role of uncertainty. For example, during delivery, the delivery man might be sick; the traffic could be particularly busy; the transport may breakdown or the weather condition might be severe etc. Alternatively, high customer demand of requesting orders for flowers might occur around the same time, such as on Valentine's Day, exceeding the capacity of the delivery team. All these potential attributes could cause delay or failure of delivery, which add extra cost not only for the refund or compensation fees for customers, but also for hiring part-time employees as a result of a staff shortage. Therefore, the challenges of applying this technique for engineering services cost estimating are not only the creation of logical rules, but also the importance of uncertainty and risk in the process of ESCE. The drawback of this approach is that it could be time-consuming and has high initial research costs. However, the greatest advantage is that it is capable of generating an optimised service offering for customers.

b2. Fuzzy Logic Systems

A fuzzy logic system is a decision table which provides system rules and indicates the relationships between the input and output variables of this system (Kumar et al., 1994; Huang et al., 2006; Attarzadeh and Ow, 2011). The main focus of this technique is its use in handling uncertain knowledge in PCE. Shehab and Abdalla (2002) developed a fuzzy model based on this approach by following several steps. These steps are fuzzification of inputs, fuzzy inference based on a defined set of rules and finally defuzzification of the inferred fuzzy values. Moreover, they have illustrated their model by giving an example of estimating the machining cost of drilling a hole. One set of rules from the decision table for hole making would be if the hole depth is large presented by an X value, the hole diameter is medium presented by a Y value, and the required surface finish, e.g. polish, presented by a Z value, then the machining time is high presented by a T value which is deduced from the relationship between X, Y and Z. Consequently, the machine cost for drilling this hole equals this machining time multiplied by the unit time cost. By applying the same concept, this fuzzy model is capable of estimating a product cost and an assembly cost. The benefits of this fuzzy logic system are competent at handling uncertainty and providing reliable estimate results. However estimating the costs of products with complex features using this approach is often time-consuming and tedious (Shehab and Abdalla, 2001; 2002).

b2. How Fuzzy Logic Systems could be used for ESCE:

This approach could be applicable for the product part of the engineering services, as the service part generally has no tangible features to estimate. However, the fundamental concept of fuzzy logic systems may be modified and adopted in services. This could be achieved by creating a fuzzy logic model to handle uncertainty in services based on their characteristics. The greatest challenge is to create a decision table for different service tasks by setting standards, such as giving rating scores for service providers' performance and customers' responsiveness, similar to supplier ratings in the 1980s (Park *et al.* 2001).

b3. Expert Systems

This technique transfers experts' knowledge through rule-based programming into a knowledge database and then selects the relevant data to infer a quicker, more consistent, and more accurate cost estimation (Chan, 2003; Datta and Roy, 2010). This approach is ideal for minimising human errors, such as different cost estimators, providing different results due to their own experience and subjective opinions. However, the noticeable drawback of this technique is that complex programming is often required (Chan, 2003). Another major limitation is that the expert system applied to PCE, which has been developed, is largely based on the theoretical techniques from textbooks rather than from the industry (Niazi *et al.* 2006).

b3. How Expert Systems could be used for ESCE:

This technique may be applicable for use in estimating the costs of services. If the expert system is capable of storing service experts' knowledge in a database, then services can be estimated in a similar way as products. To achieve this, the research question is how intangible service attributes can be transferred, such as level of co-operation between service providers and customers, into tangible criteria in the form of a standard or rating table. Therefore, the potential gap is to identify and evaluate the commonality between different types of services and hence develop a framework to estimate them. It is worth noting that the programming behind this concept could be comparably complex but may provide more accurate and consistent estimation efficiently.

Summary of applicability of Intuitive Techniques for Engineering Service Cost Estimating

Based on the summary of PCE techniques and their advantages and disadvantages and the views presented relating to the possibility of applying intuitive PCE techniques to engineering services, Table 2.2 summarises this PhDs researchers view of the way forward and possible solutions/approaches to estimate the costs for engineering services.

Table 2.2 Intuitive cost estimation techniques used on Engineering Services

Product Cost Estimation (PCE) Techniques			Engineering Services			
			Apply PCE technique to engineering services	Likely advantages in applying PCE techniques to engineering services	Likely challenges in applying PCE techniques to engineering services	Future Work to overcome challenges
Intuitive Cost Estimation Technique	Case-Based Systems		• Possible	• Save time and money for cost estimation	• Requires a great deal of historical service data • The intangibility characteristic has no physical attributes to make the comparison • Service delivery is usually a dynamic and flexible process, which makes more complex and time-consuming to build up the knowledge data base	• Identify and estimate according to differences and similarities between new services and past ones
	Decision Support Systems	Rule-based Systems	• Possible	• Capable of generating optimised service solutions	• Time-consuming • High initial research costs	• Requires to develop a rule-based algorithm/ standard for the service delivery by taking uncertainty and risk into account
		Fuzzy logic systems	• Possible	• Capable of estimating the product characteristics of an engineering service	• Time-consuming • Specially designed for estimating the costs of product features	• Develop a fuzzy logic to handle uncertainty in service
		Expert systems	• Possible	• Provide quick, more accurate and consistent estimation	• Complex programming required	• Investigate how to mimic the human expert thought process to estimate in-service cost

2.3.2 Analogical Cost Estimation Techniques

Analogical techniques utilise the similarity of products by assuming similar products have similar costs (Roy and Kerr 2003; Mittas et al., 2008). The method identifies the similarity and differences between products before adjusting differences to produce a valid and reliable estimate. This is generally achieved by the cost estimators' experience or historical databases of products. Table 2.3 summarises the analogical cost estimation techniques, which have two types of models, namely regression analysis models and back-propagation neural-network. The following sections describe these methods in detail.

Table 2.3 Analogical cost estimation methods used on products (adapted from Niazi et al. 2006)

Product Cost Estimation (PCE) Methods		Main Advantages	Main Disadvantages
Analogical Cost Estimation Techniques	Regression Analysis Model	- The method is relatively easier to use	- Incapable of solving non-linear cases
	Back Propagation neural network model	- Capable of dealing with uncertain - Possible to solve non-linear situations	- It fully depends on data to set up the model - It tends to be more expensive to set up the model

<u>*a. Regression Analysis Models*</u>

Although this method applies the same concept of analogical approach, it is only able to forecast the cost of a new product based on a linear relationship between past cases and the values of certain selected variables (Niazi *et al.* 2006; Nan, 2010). Hence, if a new product has non-linear or irregular relationships with similar products, the regression analysis model is not appropriate. Nonetheless, Hundal (1993) has illustrated that product costs can be estimated efficiently and relatively accurately based on the similarity principle, while Galorath Inc. has adopted this technique to assist the cost estimation of the airframe components (Lewis, 2000).

a. How Regression Analysis Models could be used for ESCE:

This technique can be modified and adapted to the engineering service environment. The challenge of applying this method to engineering services is to establish a linear relationship between the final service cost and the service cost attributes. For example, the respondent time of a technical problem is likely to have an impact of determining whether someone selects a machinery maintenance service. Customers could observe the waiting time in response to a particular technical problem. Therefore, it is important for manufacturing companies to understand how the respondent time affects their business. In terms of service-oriented companies ascertaining whether there is any linear relationship between their historical service costs and certain variables could be used as a basis to identify relationship for forecasting the future service costs. If this could be achieved, then the advantages would be to save time in cost estimation and at the same time produce a relatively reliable result. However, the drawback of this is that it is limited to resolving linear problems.

b. Back Propagation Neural Network (BPNN) Models

In recent years, artificial intelligence (AI) has been developed progressively for application to PCE (Bode, 1998; Smith and Mason, 1997; Chou and Tai, 2010). In particular, AI has been adapted for use in cost estimation through the application of neural networks (NNs). AI allows the NNs model to store and process data like the human thought processes so that this model is capable of inferring answers to new questions without historical data (Villarreal, 1992). This indicates that such models are particularly effective for dealing with uncertain cases and non-linear conditions (Niazi *et al.,* 2006). One of the most common types of NNs models is the back-propagation neural-network (BPNN) model. Zhang and his colleagues have used the BPNN techniques to estimate the cost of packaging products by establishing a relationship between cost and cost-related features of packaging products (Zhang *et al.*, 1996). This method not only can deal with nonlinear cases, which overcomes the limitation of progression analysis approach, but also requires less detailed data for cost estimation, which solves the common problem of traditional breakdown approaches. Although the BPNN model has several significant advantages over other methods, the major limitations are that it is heavily dependent on available data rather than experience and generally has a higher establishment cost (Niazi *et al.*, 2006).

b. How BPNN Models could be used for ESCE:

The current BPNN models may apply to the tangible part of the engineering services, however it requires further research on how to create a neural network model that can automatically infer costs to new conditions based on historical product-related and service-related attributes (Jia et al., 2009).

This approach might not be applicable for the intangible part of the engineering services; however, the concept of making a computer program learn the effect of product-related attributes in terms of cost may be modified and adopted for engineering services. To achieve this, the initial task could be to find the relationship between service costs and service-related attributes. Based on this, cost estimation software can be created which can apply the approximated function obtained from the past data to predict a cost value.

Using the summary in Table 2.3 and the views presented relating to the possibility of applying analogical PCE techniques to engineering services, Table 2.4 summarises the author's view of the way forward and possible solutions/approaches to estimate the cost for engineering services.

Table 2.4 Analogical cost estimation techniques used on the engineering services

Product Cost Estimation (PCE) Techniques		Engineering Services			
		Apply PCE technique to engineering services	**Likely advantages in applying PCE techniques to engineering services**	**Likely challenges in applying PCE techniques to engineering services**	**Future Work to overcome challenges**
Analogical Cost Estimation Techniques	Regression Analysis Model	• Might be possible but requires further work	• Saving time for cost estimation from scratch • Capable of producing a reliable result	• Limited to resolve linearity issues	• Ascertain if there is any linear relationship between historical service costs and certain variables so that the relationship could be used to forecast the future service costs
	Back Propagation neural network model	• Might be possible but requires further work	• capable of dealing with uncertain and nonlinear cases of product features	• Limited to estimating the costs of product attributes of an engineering service	• Create a model that can infer costs to new scenarios based on the relationship between service cost and past service-related attributes.

2.3.3 Parametric Cost Estimation Techniques

The parametric approach focuses on the characteristics of the product without describing it completely to estimate its cost (Duverlie and Castelain, 1999). The main principal of a parametric model is using cost estimating relationships (CERs). In aircraft the CER normally used is the weight of the aircraft, when weight increases the relevant production and utilisation cost rise. This relationship can be presented by mathematical equations, such as $Y = aX+b$ (Roy and Kerr, 2003). Within the relationship described, it is then possible use the formula to predict the cost of a future aircraft based on its weight alone. This is a simplistic example demonstrating the core idea of parametric estimating. The benefit of applying this method is utilising cost drivers effectively by considering more parameters, which overcomes the limitation of a regression analysis model (Niazi *et al.*, 2006). However, this approach does have a few down sides; for instance, CERs are sometimes too simplistic to forecast costs, affecting the accuracy of the estimation. They also rely on statistical assumptions concerning the cost driver relationships to cost, neglecting the importance of common sense, and estimators' knowledge and experience (Roy and Kerr, 2003; Sohn et al., 2009).

<u>How Parametric Techniques could be used for ESCE:</u>

However it is the author's view that the principal of the parametric method can be modified and adapted to engineering services. The questions here would be how to identify and establish the CERs for service-based businesses and especially how to transfer the intangibility characteristics into some form of tangible formula or common rules. Despite these challenges, further research on how to integrate the current parametric product model with other service approaches is also required for estimating the costs of an engineering service.

Table 2.5 shows a summary of the key advantages and disadvantages of parametric PCE techniques (adapted from Niazi *et al.*, 2006). Based on Table 2.5 and the previous discussion, the author's view on how parametric PCE techniques could be used to model engineering services is summarised in Table 2.6.

Table 2.5 Parametric cost estimation methods used on products (adapted from Niazi et al., 2006)

Product Cost Estimation (PCE) Methods	Main Advantages	Main disadvantages
Parametric Cost Estimation Techniques	- Cost drivers could take a more important role in cost estimation - Capable of producing results with high level accuracy	- Heavily reliance on cost drivers - Difficult to cost estimate accurately without knowing cost drivers clearly

Table 2.6 Parametric cost estimation techniques used on engineering services

Product Cost Estimation (PCE) Techniques	Engineering Services			
	Apply PCE technique to engineering services	**Likely advantages in applying PCE techniques to engineering services**	**Likely challenges in applying PCE techniques to engineering services**	**Future Work to overcome challenges**
Parametric Cost Estimation Techniques	- Possible but requires further work	- Utilise the cost drives effectively	- Limited use to estimate the costs of tangible features of engineering services	-Research how to identify and establish the CERs for engineering services -Study how to transfer the intangibility characteristics into some forms of tangible formula or common rules

2.3.4 Analytical Cost Estimation Techniques

Another approach that can be applied is the analytical approach, which is a quantitative cost estimation technique. The principal of this approach is to decompose the work into elementary tasks in order to estimate the product cost (Duverlie and Castelain, 1999; Khatod et al, 2010). Another more precise definition of this method is to separate a product into elementary units, operations, and activities that represent different resources consumed during the product's life cycle and deducting the final cost as a summation of all these components (Pereira et al., 1992; Niazi *et al.*, 2006). These analytical techniques can be further classified into five different categories, which are operation-based, break-down, cost tolerance, feature-based and activity based cost models. Each will be discussed in detail as followed (Table 2.7).

Table 2.7 Analytical cost estimation methods used on products (adapted from Niazi et al., 2006)

Product Cost Estimation (PCE) Methods		Main Advantages	Main Disadvantages
Analytical Cost Estimation Techniques	Operation-based cost models	- Optimised cost estimation can be obtained through different process plans	- Estimation process is often time-consuming - Heavily dependent on cost data related to detailed design and process planning
	Break-down cost models	- Has a broad costing scope - Easier estimation process without further training in computing or other software programs	- Heavily dependent on cost data related to resources consumed
	Cost tolerance models	- Capable of cost estimation effectively by applying design tolerances	- Heavily dependent on cost data related detailed design
	Feature-based cost models	- Easier to design and manufacture parts within the budget - Costs related to standard parts can be re-used for new products	- Difficult to cost estimate small and complex parts
	Activity-based cost models	- Better profitability measures - Better decision and control - Better information for controlling capacity cost	- Not all costs have a clear activity can be allocated with - Might neglect some of the product costs during the product's lifecycle - Requires high initial costs and management or accounting experience to set up and control this ABC system

a. Operation-based Cost Models

This approach is designed to estimate the manufacturing costs of a product based on the summation of costs associated with production time, non-productive time, and setup times (Jung, 2002; Jia et al., 2009). Because this type of cost model requires detailed design and process planning data, it is generally used at the later design stage of a product (Song et al., 2005; Niazi *et al.*, 2006). Nevertheless, this method is able to obtain an optimised estimation by evaluating alternative process plans, such as the mathematical model created by Feng and his colleagues (Feng *et al.*, 1996). Their cost model includes geometric features such as chamfer, rectangular blocks, holes and flat surfaces and hence, an algorithm is developed for estimating the minimum production cost of a standard part.

a. How Operation-based Cost Models could be used for ESCE:

As this technique is specially designed for estimating the manufacturing costs of a product related to machining, it is not clear how it could be applicable for estimating the costs of engineering services. Hence, it is highly unlikely that it would be simple to adapt this approach as engineering service generally focuses on providing a solution to customers with the assistance from a product rather than manufacturing the product itself.

b. Break-down Cost Models

Unlike the operation-based approach, focusing on the manufacturing costs related to machining, the break-down method tends to consider all the costs incurred during the product's lifecycle (Son, 1991). This means that costs could be associated with material, labour, and overhead costs and not just the machining. This requires even more detailed information than the operation-based approach. In addition, the break-down approach is also limited as in general it is more applicable at the final stage of product design processes, when more detail is available. However, the greatest advantages of this method are having a wider costing scope than the operation-based approach and relatively easier to apply without further training in computing or other software programs.

b. How Break-down Cost Models could be used for ESCE:

In comparison, although the break-down approach is designed to estimate the total product costs through its lifecycle, engineering service costs can also be calculated by adopting the principal of this method to some extent. In order to create a break-down engineering service model, the current challenge would be to find out all the costs incurred during the lifecycle of a product service system. If the engineering service is to provide an aeroplane to customers whenever they require and also to make sure the plane is working at a prior agreed period, then the service companies should consider all the attributes affecting the final service cost. Such attributes could be questions such as how often the aeroplane requires maintenance check; what the weather condition is on the plane's working day; has the pilot had enough experience of controlling the plane correctly and safely; what the relationship between flying mileage and plane's lifespan is? Some of these relationships can be presented by either linear or non-linear mathematical formula, but others might require a rating standard or logical deduction based on experience or historical data from the industry. The greatest challenge in applying the Work Breakdown Structure (WBS) approach is obtaining original data from industry, as cost data is generally case-sensitive and not always available. To overcome this obstacle, the research could focus on construction or other commercial industries rather than defence or aerospace domains or generate original data while keeping the information related to the data provider confidential.

c. Cost Tolerance Models

This type of techniques focuses on the design tolerances of a product to determine the product cost (Lin and Chang, 2002). It is based on obtaining the optimal tolerances before setting up the allowable boundaries for the design variables to meet certain criteria. The theory behind this tolerance cost model is primarily based on mathematical equations, closely linking the design variables and the manufacturing process. The advantage of this methodology is that cost effective design tolerances can be identified, whereas, the drawback is detailed design information is required.

c. How Cost Tolerance Models could be used for ESCE:

As this approach relies on the design tolerances of a product, it is highly unlikely to apply to engineering services.

d. Feature-based Cost Models

This approach to cost modelling identifies a product's cost-related features as a fundamental ground for determining their associated costs (Niazi *et al.*, 2006). Taking the advantages of the fast growth of 3D modelling tools, feature-based approaches have become more popular and commercial (Roy and Kerr, 2003). Therefore, a broad range of scholars have attempted to estimate the cost of products through their design, process planning and manufacturing process by using this method (Catania, 1991; Ou-Yang and Lin, 1997). It is found that products consist of standard features in terms of holes, edges, flat faces, flanges etc; hence, the lifecycle costs of the product can be determined by the summation of the cost of each feature with respect to its corresponding manufacturing process (Gayretli and Abdalla, 1999). There are several significant advantages of applying this approach to PCE. It not only allows product providers to design and manufacture parts based on design-for-cost target, but also costs related to standard parts can be re-used for new products. This means that it is likely to produce an optimise product within the budget and estimate the product cost more efficiently and effectively. However, one of the greatest obstacles to using this approach for the product costing process is that it is difficult to estimate parts with complex or very small geometric features, especially if manufacturing processes are required to produce these features (Niazi *et al.*, 2006).

d. How Feature-based Cost Models could be used for ESCE:

However, as this approach estimates cost based on product's cost related features, it is suggested that the concept might be applicable for engineering services. Because engineering services also have cost-related 'features' that could be estimated to determine their associated costs if sufficient data is obtained. The challenge of adapting this concept to ESCE is how to tangiblise intangible service features? The proposed work could be to identify different types of cost-related engineering service attributes and hence to find out the relationship between these attributes and their associated costs.

e. Activity-based Cost (ABC) Models

According to Blocher and his colleagues (2005), ABC is defined as a costing approach that focuses on estimating the costs incurred when performing the activities to manufacture a product. Each activity within the company is first identified with an associated cost and then the total cost of producing a product is a summation of all these related costs (Roy and Kerr, 2003). The main benefits this approach brings to companies are better profitability measures, better decision and control, and better information for controlling capacity cost (Blocher *et al.*, 2005; Khataie et al., 2010). Because the ABC approach is able to provide more accurate and informative product costs, this would help companies to better estimate the product profitability, improve product design and manufacturing processes, and identify and utilise any unused capacity. Although this approach has several advantages, the main problem is that not all costs have a clear activity, which they can be allocated with, such as the costs of a manager's salary, property taxes and facility insurance. Another issue is that it has the probability of neglecting some of the product costs during the product's lifecycle, such as the costs of marketing, advertising, and research and development.

e. How ABC Models could be used for ESCE:

The ABC methodology has been applied in service industry, such as the service blueprint technique created by Shostack (1984, 1987). This technique estimates the service costs based on identifying all the activities or processes of delivering a service and the associated execution time. Adapting the concept of the ABC approach to engineering services has the same benefits and limitations of applying it to a product. Companies could design an optimised engineering service within the target cost and maximise any spare capacity but might neglect some of the engineering service costs which are hard to allocate or not include engineering service activities. They also have to devote a considerable amount of time and effort to establish and monitor the ABC system, requiring high investment costs and relevant experts. The challenge of improving this technique for the engineering service costing purpose is to consider all the activities under different conditions within the in-service phase of a product service system.

Based on Table 2.7 and the views presented relating to the possibility of applying analytical PCE techniques to engineering services, Table 2.8 summarises authors' view of the way forward and possible solutions/approaches to estimate the cost for engineering services.

Table 2.8 Analytical Cost Estimation Techniques used on Engineering Services

Product Cost Estimation Techniques		Engineering Services			
		Apply PCE technique to engineering services	**Likely advantages in applying PCE techniques to engineering services**	**Likely challenges in applying PCE techniques to engineering services**	**Future Work to overcome challenges**
Analytical Cost Estimation Techniques	a. Operation-based cost models	- Not applicable as this technique is designed to estimate manufacturing costs related to machine operation	- Not applicable	- Not applicable	- Not applicable
	b. Break-down cost models	- Possible for adapting its concept	- Not applicable	- Not applicable	- Research how to estimate the total service costs by summing all the costs incurred during in-service
	c. Cost tolerance models	- Highly unlikely because this method is used to estimate costs by considering design tolerances of a product	- Not applicable	- Not applicable	- Not applicable
	d. Feature-based cost models	- Possible for adapting the concept because engineering services also have cost-related features	- Be able to obtain a detail estimated result based on service features	- Might be difficult to tangiblised intangible service features	- Identifying service cost-related features - Find relationships between service attributes and associated costs
	e. Activity-based cost models	- Possible but further work required	- Capable of designing a optimise service within the target cost - Maximise any spare capacity	- Might neglect some of the engineering service costs	- Considering all the activities under different conditions within in-service phase of a PSS is challenging and required further work

The analysis of these various techniques and their application in estimating the cost of products and engineering services identified several key findings. Using the qualitative and quantitative classification shown in figure 1, the fundamental concept of qualitative product cost estimating techniques (Intuitive and Analogical techniques) can be adapted to estimate the cost of engineering services. In contrast, the principle concepts of quantitative techniques (Parametric and Analytical) are generally applicable for estimating the costs for the product features of an engineering service, with the exception of both operation-based and cost tolerance modelling approaches.

2.4 The costing technique selected for this research – Parametrics

In this research, the parametric cost estimation technique is adapted to estimate the cost of engineering services for three reasons. The first reason for selecting parametrics is because parametrics are widely used in industry and government (Mileham et al., 1993; Cavalieri et al., 2004; NASA, 2012). Therefore, industrialists as well as academics accept the credibility and reliability of this technique. Second, parametrics can provide realistic and reliable results when cost data is meaningful and reliable (Niazi et al., 2003). In this research, the cost modelling follows by a step-by-step approach (Chapter 5) and data is obtained from a case study company (Chapter 6), hence parametrics could provide reliable and realistic cost estimates for the provision of engineering services. Third, the parametric technique can be used at the development stages as well as after-sale stages of a product (Camargo, 2003). Hence, using similar techniques from development to a product in-operation is an advantage as the users are familiar with the approach and minimal changes in the techniques would be required.

There are possible disadvantages for adapting parametrics to estimate the cost for engineering services. As the principle of parametrics is to utilise Cost Estimating Relationships and associated mathematical algorithms or logic to establish cost estimates (Parametric Cost Estimating Handbook, 2012), the major drawback is that this method relies heavily on statistical analysis techniques and thus the CERs may be too simplistic to forecast costs. To face this challenge, expert opinion as well as historical data could be considered for estimating the cost for engineering services, including modelling and validating processes. Hence, the engineering services cost model could better reflect the real system and propose cost-effective solutions for providing better services.

The next section will discuss the commercial cost estimating software, and in particular those designated for product cost estimating and PSS cost estimating. With the analysis of PSS cost estimating software, gaps and challenges for engineering service cost estimating software will be identified.

2.5 Commercial Cost Estimating Software

2.5.1 Product Cost Estimating Software

During the estimation of software development, cost has been the focus for the past twenty years (Briand et al., 1999). During this time a diverse range of cost estimating software has been designed with various applications for different domains. Among a broad selection of parametric commercial costing systems, SEER modules and PRICE systems are the most common ones (Newnes et al., 2008). SEER-DFM (2009) and SEER-H (2009) are the two types of SEER costing modules, with each focusing on the PCE at the different stages of a product's lifecycle. The lifecycle of a product can be separated into four main stages, which are the design stage, manufacturing stage, in-service stage and end of life stage. SEER-H is designed for use at both the conceptual and detail design stage, whereas SEER-DFM is developed for application at the manufacturing stages. In contrast, the PRICE system (2011) can be applied at the in-operation stage as well as the first two stages of product's lifecycle. Cost estimating mechanical and electronic components are the dominant applications for these tools. In addition, SEER systems are also capable of estimating hydraulic hardware. In essence, these tools apply parametric costing techniques, which utilise historical data to assist in the decision-making process. This means that they are favourable in predicting costs for similar products at the detailed design stage. Within PRICE and SEER systems, they consider the hardware, labour and material costs, but neglect non-recurring costs such as design time and through-life costs (Newnes et al., 2008).

Another well-known parametric costing software is the Constructive Systems Engineering Cost Model (COSYSMO) developed by Valerdi et al. (2007) based on the Constructive Cost Model (COCOMO). COSYSMO is able to estimate project's duration, staffing levels, effort and cost, as well as assisting users in obtaining an optimal project plan by making trade-offs and testing with "what-if" scenarios (Cheung et al., 2007b). COSYSMO has mainly been applied in the aerospace industry, in such companies as BAE Systems and US defence contractors (Valerdi, 2007). It also has been integrated with other commercial costing software, for instance the PRICE-H (2011), to enhance its functionality and performance.

Apart from COSYSMO, there are several costing software packages applied to the aerospace industry as well, such as the ACEIT modules (2012), and KAPES (2012).

ACEIT systems are used for analysing, developing, sharing and reporting product cost estimates, providing a structure to simplify or standardise the estimating process. They can be used at the detailed design level, manufacturing and in-service stages. They are also capable of integrating with MS-Project, Price-S, Price-H, SEER-DFM and SEER-H, which best obtain and utilise data to carry out accurate estimate. In contrast, KAPES (2012) is a manufacturing cost planning system, which helps manufacturers to determine the cost to make, buy, and sell individual components and assembled products. It is applicable not only in the aerospace industry, but also in electronics and automotive sectors. Furthermore, the system would produce comparatively accurate results at the detail design stage and manufacturing stage of a product's lifecycle.

There are various cost modelling packages designed especially for construction and building, for instance, Pulsar (2009) and LCCWare (2012). Pulsar (2009) is a premier supplier of construction cost estimating software, leading in contract preparation related to job order, delivery order and acquisition. It enables customers to negotiate and win a contract by comparing and contrasting construction bids (Pulsar, 2009). The best practice of this system is implemented at the detailed design stage and manufacturing stage of a product's lifecycle. While Pulsar software mainly deals with construction and building sectors, LCCWare software (2012) is used extensively in industries such as building, rail, nuclear power, automotive, defence and aerospace to improve safety and optimise the maintenance of plants. It is also used to estimate the life cycle cost of a system from initial design level to the end of life stage. Similarly, Relex LCC also adapts the concept of whole-life costing, which includes costs of detailed design, production, warranty, maintenance, and disposal (Cheung et al., 2009a).

In the manufacturing industry, DeccaPro (2009) and DFMA (2009) are the main costing software package being applied. DeccaPro (2009) builds cost models and price products based on the ABC technique, which helps companies to reduce bid costs, improve profitability and become more competitive in the market. However, the costing scope of this system is limited to the manufacturing and in-service stages of a product’s lifecycle. In comparison, DFMA is a cost reduction tool for product design and manufacture by analysing and comparing the costs of different materials and manufacturing methods in the design phase. This would help customers to estimate the difficulty of assembly, eliminate redundant parts and assembly tooling, and design products to minimise the manufacturing costs (DFMA, 2009).

2.5.2. Engineering Service and PSS Cost Estimating Software

The concept of through-life management, involving the provision of product-service offerings over their lifespan, has been widely adapted throughout the industry, especially in the aerospace and defence sectors (Ward and Graves, 2007). For example, Rolls-Royce plc (2009) has an extensive history of providing service support for their customers’ engines. Over the past five years, they have been upgrading their services to value-added service solutions, such as TotalCare®, CorporateCare®, MissionCare™ and Mission Ready Management Solutions®. These service offerings are no longer limited to providing traditional support such as spare parts but providing engine leasing, and predictive maintenance services including real time engine health monitoring. BAE systems (2011) have also investigated the provision of innovative through life support services, dealing with military air platforms. Their solution would cover maintenance, repair and upgrade of aircrafts while keeping minimum support costs or higher availability.

Although the concept of through-life management has been advocated throughout industries in recent years, limited commercial costing software is available for PSS, in particular for engineering service. The latest and most relevant service model related to ESCE is the CMMI-SVC model developed by the Software Engineering Institute (CMMI, 2009). This system would improve the engineering service processes by focusing on all the activities of the service provider in terms of people, procedures and methods, and tools and equipment. Although the engineering service model can help to improve various aspects of service, such as its capacity, availability and performance, it neglects the costing purpose for services. In contrast, AVICO (2009) has applied fixed price maintenance agreements to support their customers ranging from aerospace to construction domains. Hence, it shows that costing has been applied to certain aspects of engineering service, such as maintenance and repair. However, there is still a large gap in service costing to meet industrial requirements. Other costing software, such as ICCWare (2012) and Relex LCC (2009) could estimate a PSS, which mainly is product-oriented or use-oriented. It seems that there are no costing techniques for result-oriented PSS at present.

Based on analysing and evaluating the current commercial cost estimating software, a summary of various costing models applied on different product stages and different types of engineering service and PSS has been tabulated in Table 2.9. From this table, it shows that currently no cost models have been designed specifically for the service market and engineering services. This phenomenon coincides with the author's view that there is a significant gap in engineering service costing methodologies. It is this gap in knowledge that was identified and hence became the focus of this research, i.e. to estimate the cost of engineering services using parametrics.

Table 2.9 Commercial Cost Estimation Software used on Products and PSS (Adapted from Cheung et al., 2007a)

Commercial Costing Software	**Costing Software Provider**	**Domains of Applicability**	**Product**					**Product-Service System (PSS)**				
			Stage 1 Design		**Stage 2 Manufacturing**	**Stage 3 In-service**	**Stage 4 End of Life**	**Type 1**	**Type 2**	**Type 3**	**Type 4**	**Type 5**
			Concept	**Detailed**	**Facilities, Process & Logistic**	**Service & Maintenance**	**Disposal & Recycling**	**Product-oriented (product plus additional services)**	**Use-oriented (leasing model)**	**Result-oriented (selling the result or capability, not the product itself)**	**Service Oriented**	**Integration Oriented (Engineering services)**
SEER modules	www.galorath.com/	Mechanical, Electronic, Hydraulic & Structural Hardware	SEER-H	SEER-H	SEER-DFM	-	-	-	-	-	-	-
PRICE System	www.pricesystems.com/	Mechanical, Electronic Hardware	PRICE-H PRICE-M	PRICE-H PRICE-M	PRICE-H PRICE-HL PRICE-M	PRICE-H PRICE-HL PRICE-M	-	-	-	-	-	-
COSYSMO	www.cosysmo.mit.edu/	Aerospace	COSYSMO	COSYSMO	COSYSMO	-	-	-	-	-	-	-
ACEIT Family	www.aceit.com	Aerospace and Defence		ACEIT 7.0	ACEIT 7.0	ACEIT 7.0		-	-	-	-	-
KAPES	www.kapes.com/	Electronics, Aerospace and Automotive	-	KAPES	KAPES	-	-	-	-	-	-	-
Pulsar	www.estimatingsystems.com/	Construction and Building	-	Pulsar	Pulsar	-	-	-	-	-	-	-
LCCWare	www.isograph-software.com/	Building, rail, nuclear power, automotive, defence and aerospace	LCCWare	LCCWare	LCCWare	LCCWare	LCCWare	LCCWare	LCCWare	-	-	-
Relex Reliability Studio 6.0 (LCC)	www.relexsoftware.co.uk/	Any Industry apart from constructions	-	Relex LCC	Relex LCC	Relex LCC	Relex LCC	Relex LCC	Relex LCC	-	-	-
DeccaPro	www.deccansystems.com/	Manufacturing	-	-	DeccaPro	DeccaPro	-	-	-	-	-	-
Boothroyd and Dewhurst (DFMA)	www.dfma.com/	General Design & Manufacturing	DFMA	DFMA	DFMA	-	-	-	-	-	-	-
AVICO	http://www.avicoair.com/	Aviation Services	-	-	-	-	-	-	Aircraft dry lease/wet lease based on fixed price maintenance agreements	-	-	-

2.6 Summary

Section 2.1 of this chapter introduced a top-level review on product service systems, which illustrated that engineering services is a particular type of PSS - integration oriented PSS.

Section 2.2 of this chapter presented a review on product cost estimating and engineering service costing, including their definitions and costing techniques. A clear gap in the field of engineering services costing is presented. This leads to Section 2.3 of the chapter, which focuses on an assessment and analysis of how four key product cost estimation techniques namely; intuitive, analogical, parametric and analytical could be enhanced/adapted to estimate the costs for an engineering service. The main findings are summarised in four tables (2.2, 2.4, 2.6 and 2.8) where the researcher considers whether the product costing technique would be applicable for estimating the cost of engineering services and which modelling approaches within these techniques could be used.

In Section 2.4 of the chapter, parametrics is selected for estimating the cost for engineering services in this thesis. The reasons for selection are justified, possible disadvantages are highlighted and proposed solutions are provided.

Section 2.5 of this chapter presented a review of the literature on cost estimating software, in particular product and PSS cost estimating tools. The analysis of various commercial software packages and their application in estimating the cost of products and engineering services identified the key gaps. It is found that limited software is designed for estimating the costs of an engineering service. Hence, there is a clear gap in identifying cost estimating techniques and software to predict the cost of an engineering service.

The outcome of this costing review has identified that engineering services is a particular type of PSS, and a number of product cost estimation techniques and tools can be enhanced/adapted to ascertain appropriate approaches for estimating the cost of an engineering service.

For the research presented in this thesis, the parametric cost estimating technique is adapted to estimate the cost for engineering services. As the parametric approach focuses on identifying the Cost Estimating Relationships between costs and cost-related attributes, the next stage of the research was to identify case study partners which could guarantee access to the cost-related data and experienced experts. In the next chapter, an industrial survey is conducted to ascertain the way that industry estimates the cost for engineering services and seek for potential case study partners.

Chapter 3 Industrial Practice

Chapter 2 provided a review of the academic literature and public domain documentation. The outcome being that using the parametric technique for predicting the cost of engineering services was appropriate. However, the literature did not offer findings on current industrial practice.

Within this chapter, two areas of industrial practice are presented. First, the findings from an industrial survey conducted by the PhD researcher to ascertain the way that industries estimate the cost for engineering services is provided. The aim of this survey was to ascertain current practise as well as identify potential case study partners.

As part of the findings of the survey and informal discussions with industry, the author identified that the bathtub failure model and its use within reliability modelling was a technique that the industrial community were familiar with. From the results of the survey and the initial industry discussions the author believed that it could be possible to utilise such an approach to estimate the cost of engineering services.

Second, this chapter presents the findings from a review of the literature on bathtub failure models to ascertain whether there was any cost estimation of systems using such an approach. Little solid empirical evidence was found to demonstrate that a machine level system followed the bathtub failure model and that such approaches had been used to estimate the cost of providing engineering services.

It is this gap in knowledge that was identified and hence became the focus of this research i.e. to estimate the cost of engineering services using parametrics and the bathtub failure model.

3.1 Industrial Survey

In the literature review (Chapter 2) the author identified that there is a gap in the field of costing rules and models for predicting the cost of engineering services. The author also proposed that parametrics could be used to estimate the cost of engineering services. To test this proposal, a suitable case study was required in terms of exploring industrial context, accessing experts and collecting historical data. To identify suitable companies the researcher undertook an industrial survey with the aim of identifying companies that were interested in the research activity and would allow suitable access to their facilities, records and staff.

The questionnaire (Appendix A) was designed based on findings from the literature reviewed in Chapter 2. The industrial survey was designed to provide two outcomes. First, to ascertain the current state-of-the-art in an industrial context, with an emphasis on how the cost of engineering services is estimated. Second, and more importantly, the survey was used to identify possible case study partners. To achieve these outcomes the objectives of the questionnaire were to ascertain the following information:

1. The background of the industrial company
2. The position of the industrial respondents
3. To find out whether companies differentiate between products and services
4. To discover whether companies understand how to estimate the costs for providing engineering services

The questionnaire (questions only) was prepared in a word document and e-mailed to twenty named industrial contacts. These respondents were mainly from the defence and aerospace sectors and included companies/customers such as the MoD, BAE Systems and Rolls-Royce. The contacts were requested to e-mail the competed questionnaire back to the investigator for analysis within an agreeable period of six weeks.

By the deadline, four out of twenty questionnaires were completed. Tables 3.1a and b provide a summary of the results from the industrial survey. The respondents were all cost estimating experts, including three with more than 10 years experience and one with 3-5 years experience. They all work in well-known multinational companies that provided both extensive product and engineering services to customers in the UK as well as globally.

Table 3.1a Industrial survey questions 1-8 and findings

Questions	Findings (from four cost estimating experts)
1. How many years of experience do you have in cost estimating?	• 1 with 3-5 years experience, 1 with 10-20 years experience and 2 with more than 20 years experience
2. Which of the following category does your company belong to?	• All respondents worked in companies that offer integrated products and services
3. What is the scale of product and engineering services offered in your company by revenue?	• Based on revenue, companies offered an average 50% product and 50% engineering services
4. Do you explicitly cost estimate product and engineering services differently?	• Three out of four recognised there is a difference between product costing and engineering services costing, however they could not explicitly indicate the differences
5. Does your company offer engineering services?	• Four companies offered services via through life support and service contracts. One of these companies provided availability contracts.
6. Do you do costing for engineering services using product costing tools?	• Four cost estimating experts use product costing tool to estimate the cost for engineering services and one expert stated that there is a challenge on predicting the cost for long-term engineering service contracts
7. Does your company involve customers as part of the co-creation of value? Do you measure your customers' input to the process?	• Four companies involved customers as part of the co-creation of value via, e.g. design stage of the solution or service contract negotiation and finalised stage. • One expert (more than 20 years experience) measured the customers' input to the value co-creation process and the challenge was to identify all customers' inputs and to model the solution with enough accuracy. • Two experts did not measure the customers' inputs and one expert did not fill in this sub-question.
8. The table shows a spectrum of cost estimation techniques. Please fill in the table as required (Appendix A).	• Three experts had experience of using the four most common types of product costing techniques, namely intuitive, analogical, parametric and analytical. One expert had experience of using the first three techniques. • Common costing software that the respondents used was Excel, PRICE and SEER. • Key challenges that experts faced are lack of detailed cost data, the costing approach is highly complex and hard to see how the results come from the inputs.

Table 3.1b Industrial survey questions 9-12 and findings

Questions	Findings (from four cost estimating experts)
9. Which cost modeling types have you had experience of using?	• One expert had experienced in using only engineering services cost models, whereas three experts had experienced using both product and engineering services cost models • Based on the three experts opinions, they confirmed that engineering services costing is closely related to product costing. However the focus and key drivers for estimating the cost of engineering services may be different from product cost estimating.
10. Forecasting is commonly used in cost modelling. Please indicate all the type of things you forecast and the basis or process for generating your forecast.	• Maintenance costs are estimated based on past experience and could be used to predict future cost (one expert's opinion) • To predict the future cost for engineering services based on assumptions (one expert's opinion) • Forecasting for complex systems from different aspects, i.e., technical, economic, and supply chain. (two experts' opinions)
11. Does your company use cost modelling for estimating engineering services costs?	• All of the four respondents used common product costing techniques and software to estimate the engineering services costs
12. Do you use service blueprint to design the engineering services process?	• One expert adapts the service blueprint to design engineering services process • Two experts use other methods, such as customer survey and value stream mapping, to design the engineering services process • One expert did not fill in this question

From the responses (Tables 3.1a and b), the key findings from this survey are:

- Three out of four cost estimating experts recognised that there is a difference between products and engineering services, however they could not explicitly define what they were. This may affect the reliability of the costing results when product costing techniques or software is used to predict the future cost of engineering services.

- All the experts used product costing techniques and software to model the future cost of engineering services. This matched with the findings from the literature review (Chapter 2) and showed that there is a clear gap in the field of cost estimating for engineering services.

- The current challenges that cost estimating experts faced were a lack of historical cost-related data and that costing engineering services is very complex. It was also noted that it was not clear how the results from the models were achieved, i.e. how the results relate/link to the inputs to the model. This clarifies the need to create a step-by-step approach for estimating the cost of engineering services transparently, efficiently and effectively. In addition, one cost estimating expert stated that there is a challenge for estimating the cost of providing long-term engineering service contracts.

From the four completed questionnaires, it was found that many questions were only partially answered. Apart from confidential and sensitive reasons, the main reason that a limited number of interviewees partially completed the questions was that the respondents did not know how to easily estimate the cost for engineering services. In other words they could not initially identify an effective and time efficient approach. Dr Newnes and the researcher discussed with some of the respondents what the challenges were.

The informal discussions found that many of the respondents had struggled answering the questions; in particular because the cost estimating questions covered aspects from different perspectives of a company. The respondents were unable to allocate adequate resources to complete the questionnaire effectively. For example, historical costing questions in some cases required answers from the Finance department, whereas, costing techniques in general would be provided/answered by the Engineering department. The industrial contracts also acknowledged that estimating the engineering services costs for their assets was an area they found challenging.

Based on the semi-completed questionnaires and the informal discussions two conclusions were reached. First, industry recognised that this was an important area and realised that further research was required. Second, it was important to select a case study company, which not only could access the cost-related data from different departments but also had close contacts with staff from different divisions.

Meanwhile, it was also important to recognise that the reason for conducting this research was to collect and analyse cost data in order to estimate the costs of engineering services by using parametrics. However, it was considerably difficult to collect sensitive and confidential cost data from industrial companies. Cost data normally includes internal information about a company, such as its profit margin, strengths, weaknesses, and labour costs, which were highly unlikely to be exposed extensively to the outsiders. Even within the company, different stakeholders within the company may keep key cost data. Hence, due to the nature of this research, it was comparatively difficult to find open and robust case studies.

To test the aim estimating the cost of engineering services using parametrics and the bathtub failure model, it was necessary to have open access to internal company data. Hence to meet the research requirements the researcher chose to work with a Chinese company where she had personal contacts and could guarantee getting access to the data they held (Chapter 6).

However, although the survey did not provide a case study example, the discussions with industry did lead to key questions in relation to the use of the bathtub failure model and whether this could be utilised to predict the engineering services cost for a system. It was known that the bathtub failure model could be used to predict the failure rate for common repairable components or subsystems of a machine (Moss, 1985; Carer et al., 2004; Spinato et al., 2008). One question was whether the failure pattern for the entire machine followed a similar bathtub failure curve. If the answer was positive, the other question was whether the bathtub failure model could be used to predict the costs for providing engineering services for machines.

The next section reviews the literature on machine (system rather than sub-system) reliability related to the bathtub failure model and whether it is appropriate for consideration when estimating the cost of engineering services.

3.2 Machine Reliability – Bathtub Failure Model

In the field of reliability, the failure pattern for repairable machines is often represented by the bathtub curve (Andrews and Moss, 1993; Qi et al., 2003; Wilkins, 2002). From Figure 3.1, the bathtub curve consists of three phases. In phase I at the early stage of a machine, the failure rate reduces dramatically as time increases. This is because weak components may be replaced or fixed during this period (Andrews and Moss, 1993). This decreasing failure period could be varied to different types of machines, lasting for weeks, months or years (NIST/SEMATECH, 2012). In phase II at the useful life of a machine, the failure rate remains approximately constant as time increases. In phase III at the end life of a machine, the failure rate increases significantly as time increase. This occurs as the machine started to deteriorate, such as components are degraded or materials are worn out. The bathtub curve is referred as the bathtub failure model throughout the thesis.

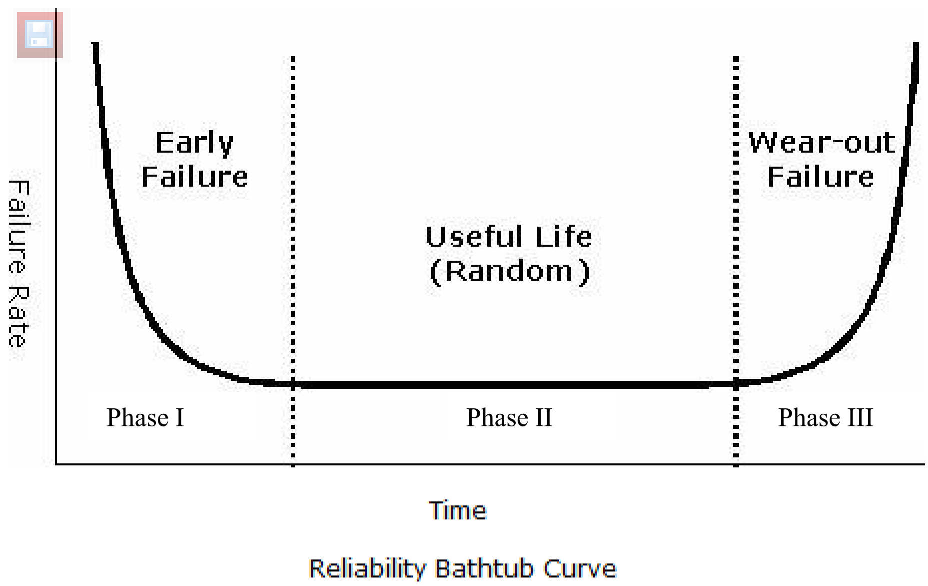

Figure 3.1 Reliability bathtub curve (Andrews and Moss, 1993)

It was found that the bathtub failure model has been utilised in different sectors, such as in aerospace, electronics, machinery and wind turbines (Aarset, 1997; Wallace et al., 2000; Klutke et al., 2003; Spinato et al., 2008). However, there is considerable debate on its applicability (Klutke et al., 2003; Aarset, 1997; Spinato et al., 2008; Wallace et al., 2000). Mak (1987) stated that the failure rate for replaced components of remote devices for load management was coincided with the bathtub failure model. This matched with Andrews and Moss's view (1993) that the reliability characteristics of most component families follow the bathtub failure model.

In contrast, NIST/SEMATECH (2012) claim that the failure pattern for most products yield such curves, although they do not provide examples of such products. Thus, the term "product" was unclear, which could be a component, sub-system or system. Although Qi and his colleagues (2003) state the bathtub failure model could be used to describe the process of failure for an aeroplane, it was hard to use as the basis for providing maintenance service contracts due to the complexity of the plane and difficulty of accessing essential data. This viewpoint is similar to Wallace and his colleagues (2000).

Moreover, Moss (1985) suggested that the bathtub failure model could model the reliability characteristics of a generic piece-part type, but not of an assembly, a circuit or a system. Spinato and his colleagues (2008) agreed with this viewpoint, as they investigated the failure rate of different subassemblies for wind turbines by considering the bathtub failure model. It showed that the converter, generator and gearbox were at different phases of the bathtub failure model. Similarly, Carer and his colleagues (2004) showed that the failure rate of electrical equipment, such as that of city street lamps followed a bathtub model.

3.3 Summary

Based on the findings from the literature it is the author's view that the existing literature has little compelling empirical evidence to prove that the machine level system follows the bathtub failure model (Moss, 1985; Klutke et al., 2003). It is this gap in knowledge that provides the focus of this research. In other words ascertain whether the bathtub failure model can be used to estimate the cost for engineering services.

Hence, combining the findings from Chapter 2, the overall aim of this research is to estimate the cost of engineering services using parametrics and the bathtub failure model.

In the next chapter, methodology and research methods will be presented to ensure the aim and objectives of this research are attained.

Chapter 4 Scope of research and outline of methodology

From the analysis presented in chapters 2 and 3, it was showed that there are clear gaps in knowledge on how to estimate the cost of engineering services. The approach proposed to address this based on the findings from the literature and a review of current practice was the use of parametrics and the bathtub failure model, which is the focus of the research presented in this thesis. This chapter describes the overall aim and objectives for the research. The research methodology and the selected methods that were used to meet these aims and objectives are then presented.

4.1 Research Aim

To fill the identified gap in knowledge, the overall aim of this research was to estimate the cost of engineering services by using parametrics and the bathtub failure model.

4.2 Research Objectives

To meet the aim of the research, the following specific objectives were defined.

1) Select an industrial case study, collect and analyse historical data from the case study company.
2) Create an engineering services cost model for the case study company.
3) Validate the engineering services cost model.
4) Test service scenarios and propose service solutions with associated costing.

4.3 Research Methodology

This section presents a discussion and critique of the overall research methodology, followed by a discussion of the methods that were selected for use at the different stages of the research.

Research methodology may be viewed and applied differently according to a specific discipline or context (Rajasekar et al., 2006; Blessing and Chakrabarti, 2009). This chapter focuses on the methodology that was relevant and applicable for this research.

In the design domain, approaches, methods, and guidelines are the core idea of framing a methodology (Blessing and Chakrabarti, 2009; Zhong and Liu, 2010). Methodology can be described as "*a system of methods used in a particular area of study or activity*" (Oxford English Dictionary, 2009; Hain and Back, 2011). Rajasekar and his colleagues (2006) enhanced the viewpoint by suggesting methodology as a systematic approach to solve a problem.

Blessing and Chakrabarti (2009) propose an approach for use in engineering design. They state that the research methodology may be separated into four stages: research clarification, descriptive study I, prescriptive study and descriptive study II. Their approach presents a generic process. Although the author used this to understand the initial research clarification, it was not utilised further.

In contrast, the step-by-step approach developed by Kumar (2005) was more user-friendly. It offered a clear structure and easy to follow steps as well as being able to be customised to suit individual case studies. Thus, by adapting Kumar's approach (2005) the overall research methodology utilised for this research is shown in Figure 4.1, indicating where the overall aim and defined objectives of this research fit. Each step of Figure 4.1 matches with a chapter of the thesis. The dotted boxes in Figure 4.1 highlight the main focus of the research presented in this thesis.

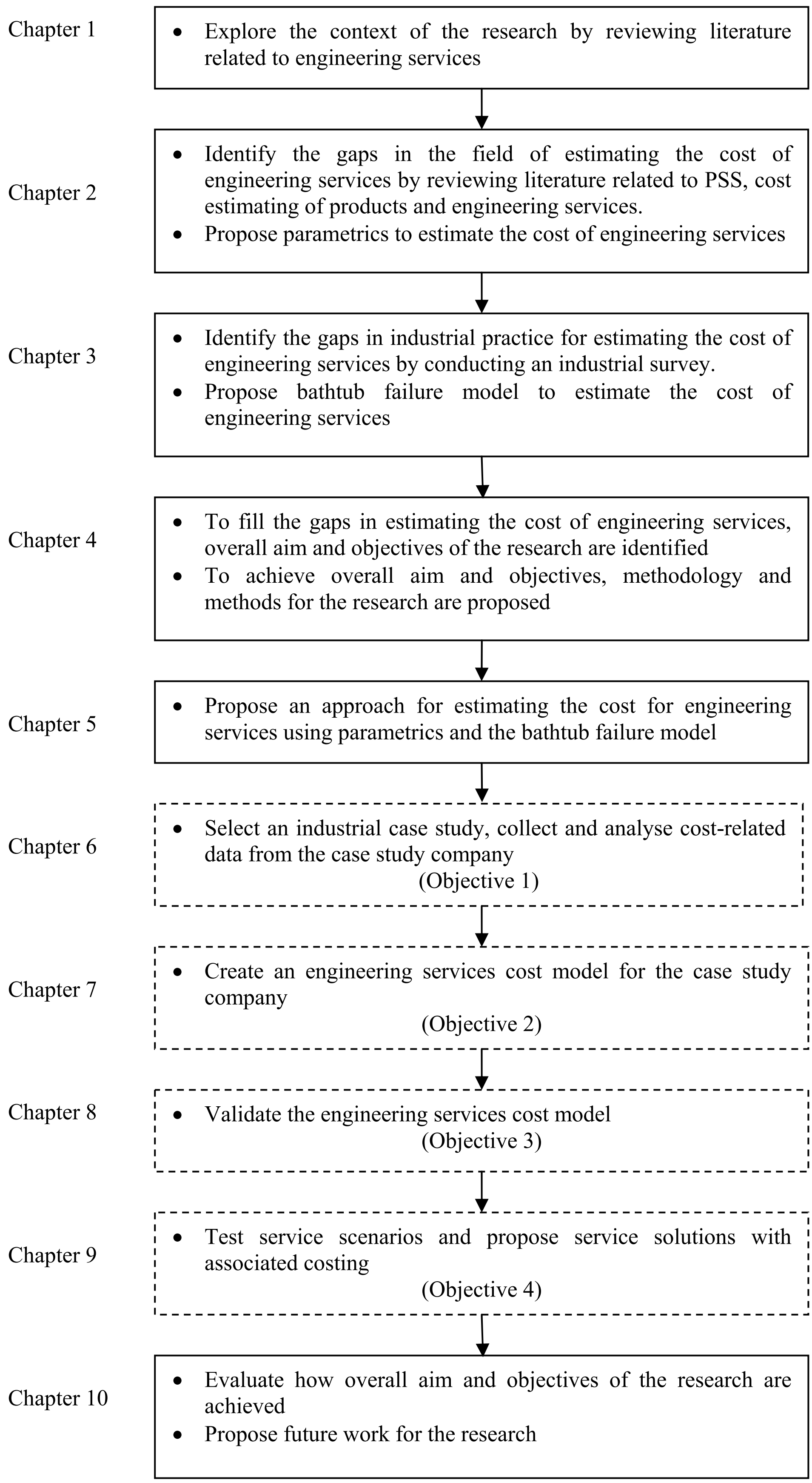

Figure 4.1 Overall research methodology and focus (adapted from Kumar, 2005)

In parallel with the design research methodology, ontology, epistemology and theory form the fundamental basis of defining social research methodology (Turnbull, 2002; Brannen, 2005; Herrman, 2009). While conducting social research, a consistent structure and principle were applied during the development or validation process (Herrman 2009; Wolfenstetter, 2011). Guba and Lincoln (1994) then expanded on this view and define the methods in terms of how they were conducted to generate the type of knowledge associated with a particular research paradigm.

In terms of a detailed research methodology, social research methodology was adapted because the costs of an engineering service depend on different paradigms, which may influence the assumptions, approaches and methods adapted for this research. For example, the development and validation of an engineering services cost model might depend on sets of epistemological assumptions.

Since it is essential to have a clear and consistent methodology throughout the research, a detailed methodology for the focus of this research was developed based on the author's ontology and epistemology positions.

The author's ontology comes from the positivist perspective reflecting the nature of the subject of this study – engineering services costing. The positivist approach takes an objective position regarding the phenomenon being studied. In this research this equates to having an objective reality, which means the observers are independent and should have no influence on the subject being studied (Bryman, 2008; Herrman, 2009). As a researcher the author is objective to the costing phenomenon, and the costing model and corresponding results will be subsequently independent from her own perception. To articulate the authors understanding of the world, her positivist epistemology places emphasis on generating and testing CERs empirically in order to confirm it or show the need for modification of the costing theory.

4.4 Research Methods

Within this section, a general background of the research methods is presented. Appropriate methods are then selected and described in detail.

Research methods are generally classified as qualitative, quantitative or mixed methods (Thompson, 2004; Brannen, 2005; Creswell, 2009). Qualitative research is often associated with words or open-ended questions, whereas quantitative research generally deals with numbers or closed-ended questions. Mixed methods research incorporates a combination of qualitative and quantitative.

Qualitative research is commonly used for exploring and understanding a social or human problem from an individual or group point of view, whereas, quantitative research is more often applied to test objective theories by examining the relationship among variables (Huang, 1996; Niglas, 2004; Creswell, 2009). The former strategy could be frequently applied to a new area for which there is only limited information available to guide research. It follows an inductive logic, which focuses on interpreting individual meanings to explain or solve complex situations (Creswell, 2007). By contrast, a quantitative approach tends to follow a deductive logic, which emphasises the testing of a hypothesis through experiments (Kung, 2004). This is generally used to research an area, which is based on comparatively sufficient data or past experience.

The field of engineering services cost estimation is a relatively new area which uses data that is normally confidential among companies. There is also limited academic work within this domain. Therefore, a qualitative research strategy would appear to be more appropriate to adapt for this research. However, as much of the past academic work has been focused on product cost estimation and product and engineering service have certain similarities, the author suggested that product cost estimation techniques or methods may be adapted to estimate some part of an engineering service. Thus, a relatively smaller proportion of the research design would be quantitative with closed-ended questions to test this hypothesis.

Based on the methods that could be adopted, the application area and the aim of the research, the strategy of mixed methods research, with a focus on qualitative research has been selected. This offers the benefit of taking advantage of both research strategies, as well as helping to generate a thorough and broad picture of the engineering services cost estimation sector.

As this research mainly depends on cost-related data, various mixed methods have been implemented to focus on collecting this type of data. The author selected XX Company as a single longitudinal case study, working closely to collect historical data. The background of the company will be introduced in chapter 6. Historical sources, structured meetings and questionnaires are the three key methods of collecting primary data for this research. Figure 4.2 show a summary of different methods of data collection. Three methods were used within this research. The next sections will describe the reasons for selecting these methods and the overall approach used. The three methods were not to be interpreted as a set of stages to be completed rigidly and linearly. They could be adapted to stages and situations whichever were appropriate, that means they might be utilised more than once or used in parallel. In addition, chapter 6 describes the use of the methods in detail and how the data was analysed.

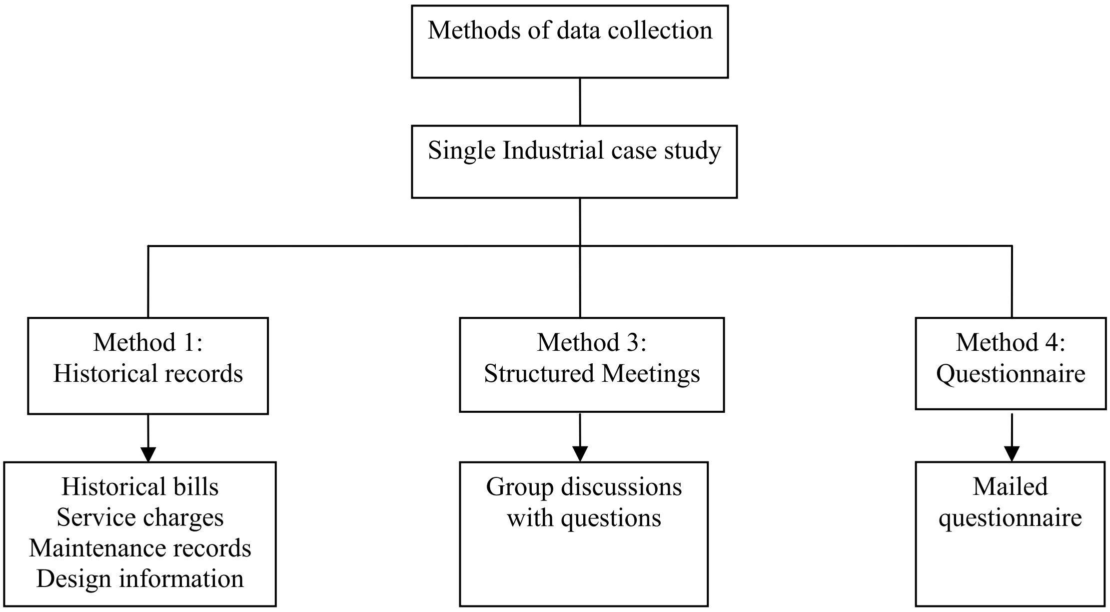

Figure 4.2 A summary of different methods of data collection

4.4.1 Method 1: Collecting historical data

Case studies are often seen as the prime example of qualitative methods – which study the data given by respondents and interpreted within context. It is usually used to answer "why" and "how" questions, while the researcher has difficulty controlling events and the focus is on real-life situations (Yin, 2003). There are also other qualitative methodologies such as ethnography, grounded theory and narrative research (Creswell, 2009). Since this research focuses on seeking how engineering service cost estimation is similar and different from product cost estimation, case studies would be the preferable methodology applied. This strategy allows a variety of data collection procedures to be used over a period of time to collect detailed information (Stake, 1995). This means that the research can utilise various methods depending on different circumstances or special requests to generate more in-depth research (Gummesson, 1991; Denscombe, 1998; Flyvbjerg, 2006). For example, if the researcher intended to find out whether a company explicitly cost estimates product and service offerings differently, they could not only ask this question directly to respondents to obtain a "yes" or "no" answer but also ask them to indicate the differences. Hence, detailed information would be generated for further analysis.

The author made four visits in the XX Company, collaborating closely with the company to collect and analyse data. Eight years of service related cost data such as historical bills, service charges, maintenance records, and costs for storage has been collected. Because this data all has a hard copy as evidence and has been collected directly from the company by the author, the reliability of these data is relatively high. Moreover, any missing or unclear data has been explained and justified by the data recorder to ensure the validity of these data. The data issues will be discussed thoroughly in chapter 6. Therefore, this eight years of cost-related data could be a reliable and validated source to form the basis of generating engineering services costing rules or relationships, and testing and validating the engineering services cost model.

4.4.2 Method 2: Conducting structured meetings

In terms of the quantitative methods applicable for this research, experiments and surveys have been identified. Experimental research seeks to determine whether one particular input influences an output, whilst a survey tends to quantitatively or numerically describe a particular pattern or attitudes of opinions of a larger population from the drawn sample (Creswell, 2009). One objective of this research was to find trends during machine breakdown, such as the likelihood of a machine to breakdown. A survey research methodology seems more appropriate to implement for the quantitative part of this research. Based on Bryman (2008), a survey can be categorised into structured meetings and self-completion questionnaire.

In terms of structured meetings, group discussions are proposed to be carried out with experienced maintenance staff and financial staff within the case study company (the seller and the service provider). Here the aim is to ascertain whether the results from the meetings match the historical data as well as predict the future trends of machine failure rate. The benefit of conducting structured meetings with prepared questionnaires is that the respondents would have a better understanding of the questions and more likely to provide instinctive and honest answers (Kung, 2004; Blessing and Chakrabarti, 2009). However, the major disadvantages of this technique is that not only time-consuming, but more importantly, the researcher might influence the respondents unintentionally (Brannen, 2005).

4.4.3 Method 3: Conducting self-completion questionnaires

In parallel to the structured meetings three sets of self-completion questionnaires were planned to be conducted at various stages during the research. First, an industry survey was conducted to ascertain the way that industries estimate the cost of engineering services and identify potential case study partners (Chapter 3).

Second, the maintenance staff of the Case Study Company completed the questionnaires after the initial research. These were undertaken to ascertain specific engineering services detail for use within the engineering services cost modelling development (chapter 6).

The third set of questionnaires targeted both the maintenance staff and financial staff within the case study company. They were conducted in the structured meetings during the model's validation stage. The main purpose was to validate the process and logic of the engineering services cost model. Discussions about this questionnaire will be presented in chapter 8.

The advantage of applying self-completion questionnaires is that they can provide large amounts of data from respondent across regions at a relatively low cost. It could also help to capture information that was not recorded, as well as obtain insights from the customers' point of view. It avoids face-to-face contact, which minimises the influence an investigator has on respondents; thus, increases the credibility of the survey. Moreover, because each respondent is ensured to face exactly the same set of questions, the results obtained from self-completion questionnaires may be less subjective than those from face-to-face interview. This may minimise the influence of researcher to interviewees. However, the major disadvantages of conducting a survey are that respondents may misinterpret the questions or not tell the truth about controversial questions. Moreover, it could be time consuming and costly for completing the survey within a moderate scale of sample (Glasow, 2005).

In summary, the investigator for this research is adopting a positivist approach as the main position of the research, with mixed methods. Case study, semi-structured meetings and self-completion questionnaires are the key methods adapted to explore the engineering services cost estimation industry to clarify the challenges for the research activity. The next chapter will present a step-by-step approach for estimating the cost for engineering services.

Chapter 5 An approach for estimating the cost for engineering services

To achieve the overall aim of this research, an approach for estimating the cost for engineering services using parametrics and the bathtub failure model is proposed. This chapter discusses the proposed approach. Chapters 6-9 then describe each step of the approach in detail and in the context of the case study.

5.1 An approach for estimating the cost for engineering services

From Figure 5.1, the approach is separated into four steps.

Step 1) An industrial case study company is selected (Chapter 6). Reasons for selecting a particular case study are provided and justified. The background of the company is researched, in particular the types of engineering services that they offer and the possible challenges for providing such services. Historical cost data, such as bills, maintenance record and service charges, are collected and analysed. A questionnaire is also conducted with a group of maintenance staff within the company. If this process is being adopted within a company, the company selection would be replaced by 'engineering services provision, or product range for engineering services', depending on the company environment. However, the process of data collecting and questionnaires would still be undertaken.

Step 2) An engineering services cost model is created (Chapter 7). First, the scope and process of the engineering services cost model is determined. This ensures the logic and boundaries of building the model are structured and clear. Second, based on historical data collected from the case study company, performance factors for machine breakdown are identified and Cost Estimating Relationships for providing engineering services are then generated. The turning points for the bathtub failure model should also be identified to enable these to be used as a Cost Estimating Relationship i.e. identify based on the data where the early failure rates occur, when the machine moves into the useful life stage and finally when the wear-out failure phase begins. This shows the principle of the engineering services cost model as well as the process of creating the model.

Step 3) The engineering service cost model is validated (Chapter 8). Initially the concept and the principle of creating the cost model are validated by two groups of experienced experts. Further validation is then undertaken by splitting the machine data into mechanical and electrical data.

Step 4) Service scenarios are tested and service solutions with associated costing are proposed (Chapter 9). Two service scenarios are provided. First, how to price an engineering service contract based on 1, 3, 5, 7, 9, 11, 13 and 15 years in operation. Service solutions, in particular costing strategies are discussed. Second, how to allocate on-site staff based on the number of machines in-operation is tested. The benefits, service strategies, potential problems and proposed solutions for the second scenario are then discussed.

1. Select an industrial case study (Chapter 6)
- Reasons for selecting the case study company
- Research the background of the case study company
- Collect and analyse historical cost data from the case study company

2. Create an engineering services cost model (Chapter 7)
- Identify the scope and process of engineering services cost modelling
- Identify performance factors and CERs of the engineering services cost model
- Apply the bathtub failure model and stage within the bathtub using the historical data

3. Validate the engineering services cost model (Chapter 8)
- Validate the concept and principles of the engineering services cost model using experts opinions
- Validate the engineering services cost model by splitting the machine data into mechanical and electrical data

4. Test service scenarios and propose service solutions with associated costing (Chapter 9)
- Propose how to price an engineering service contract based on 1, 3, 5, 7, 9, 11, 13 and 15 years in operation
- Propose how to allocate on-site staff based on the number of machines in operation

Figure 5.1 An approach for estimating the cost for engineering services using parametrics and the bathtub failure model

The proposed approach was derived from the industrial findings and the need identified from the literature review to offer a clear guide on the steps required to estimate the cost of providing engineering services.

The findings from the literature to use parametrics and the industrial steer in utilising the bathtub failure model are reflected in the four steps. The next chapter will discuss the industrial case study company, including reasons for selecting a particular case study and the background of the company. Based on the case study company, historical cost-related data as well as questionnaire data from maintenance staff are collected and analysed.

Chapter 6 The Industrial Case Study Company

To illustrate the first step of the approach described in Chapter 5 (Figure 5.1), the industrial company that was used to create an engineering services cost model is described. The reasons why the company was selected and the advantages and disadvantages of this selection are discussed. The company background is introduced followed by discussions of the types of engineering services that the company offers, the key challenges they currently have and why they are interested in estimating the costs of providing engineering services. More importantly, how cost related data were collected through the industrial company is presented. A summary and a detailed discussion about the collected data is presented and analysed.

6.1 Case Study Selection

This section describes why the particular case study was selected, and the advantages and drawbacks of this selection.

6.1.1 Case Study Company

The aim of the case study was to undertake a longitudinal study to collect and analyse cost-related data, which could be used to create an engineering service cost model. To meet this requirement, access to experts, historical data and an understanding of the industrial context was required. To identify suitable companies the researcher undertook an industrial survey with the aim of identifying companies that were interested in the research activity and would allow suitable access to their facilities, records and staff (Chapter 3). However, due to the nature of this research, no case study partners were selected from the industrial survey as they were unable to offer the required access to data and staff.

Hence to meet the research requirements the researcher chose to work with a company where she had personal contacts and could guarantee getting access to the data they held. The reasons for selecting the following case study company are described in the following sections.

The researcher has a personal relationship with the owner of a Chinese manufacturing company, which for reasons of confidentiality will be named XX. It is a private limited company, which has around 130 staff and nearly 18 years of history. This showed that the company had a reasonable size and year length, which could be researched.

Although the company is not a large-scale multinational company, it is a leading manufacturer and service provider of XX machines in China. They also provide engineering services type b) as depicted in Table 1.1, i.e. they focus on offering both products and product-oriented services, which is the type of engineering services being studied within this research. The company has a well-known reputation of providing XX machine-related services in the packaging industry. For example, the company owns various invention patents on XX machines and set standards for designing and manufacturing XX machines in the Chinese industry. Up to 2009, the company has sold hundreds of machines around the world and delivered machines and engineering services for famous national firms as well as large multinational companies. In addition, the company is a member of the national packaging federation and association. It also worked closely with universities and has the post-doctoral scientific research station for a famous university in China. Hence, XX Company is a reliable and sustainable company, which provides high quality machines and engineering services.

More importantly, the company had eight years of service-related data, which spanned from 2003-2011. This data fits with the focus of this research – estimating the costs of engineering services. Due to the personal connection, the researcher was able to access historical and up-to-date cost-related service data as well as contact managers from different departments in XX Company. The researcher was also able to conduct surveys with maintenance staff as well as customers. Therefore, apart from the eight years of historical data, the researcher was able to obtain first-hand information through structured meetings and questionnaires. These were used to compliment the physical data with the engineering context information.

Therefore, since no other case studies could be found during this research, the XX Company was selected as a single longitudinal industrial case study to be researched.

The data and information gathered from the company have acted as a basis for creating an engineering services cost model. Advantages and drawbacks of selecting a single case study are presented in the following section.

6.1.2 Advantages and disadvantages for selecting XX Company

The advantages for selecting XX Company as a single case study are defined by Sarantakos (2005) and Flyvbjerg (2006).

- This single case study research enabled an in-depth analysis, as eight years of cost-related data were collected as well as first-hand information generated from different sources.
- A longitudinal case study can provide very valuable information for a specific situation. In this case, understanding how to estimate the costs of servicing XX machines.
- The approach for XX Company to estimate the costs of an engineering service may provide valuable guidance to other engineering service companies.

Disadvantages for selecting XX Company as a single case study are defined by Sarantakos (2005) and Flyvbjerg (2006).

- The breadth of single case study research may be narrower than that of multiple case studies research.
- The results generated from one case study might be less persuasive and convincing than those developed from multiple case studies.
- The theoretical relationships and the service cost model generated from this case study may not be able to apply for other case studies.

Although there were both advantages and disadvantages of selecting the XX Company for the case study exemplar it was felt that the disadvantages could be managed, in particular, through utilising multiple data sources. This will be discussed in detail in Section 6.3.

The background of this company will be presented in the next section. In particular, what types of engineering service this company provides, what challenges they face and why they are looking at the cost for engineering services are discussed.

6.2 Industrial Company Background

The XX Company is a machine and service provider of XX machines in China with annual revenue of £5-6 million. It is located in the south of China. It is one of the dominant manufacturers in designing and producing XX machines in China. These machines have been sold not only in China, but also to other countries, such as India, Japan and Russia. The machines are widely used to produce fast food and drink sterile packaging materials.

6.2.1 Engineering Service Offering by the XX Company

Apart from designing and selling these machines, XX offers an extensive range of after-sales services to both home and overseas customers. In this context after-sales service means that the XX Company provides engineering services after the machine is sold. Hence, after-sales service and engineering services are used interchangeably throughout the thesis. Table 6.1 summarises the types of engineering services and the associated charge, XX offers. XX explicitly classifies what service activities are provided during and outside the warranty period. XX Company offers a one-year warranty for the XX machine to their customers. This means that any machine breakdown, which occurs during this period, XX staff promise to provide phone service, e-mail service or site service whichever is more appropriated and efficient for the customer. These services are provided to customers free of charge. Any costs associated with the service, including costs of labour, transportation, accommodation and beverage are on the XX Company's account. In addition to providing free service during the warranty period, XX staff aim to provide a response within 24 hours and visit the customers' company within 72 hours for mainland customers enquiries. Furthermore, overseas customers are treated in the same way except that XX staff would deal with overseas customers' technical problems within 5 days after they obtain an entry visa to the customer's country.

In addition, not only does XX Company provide service guarantees during the warranty period, they provide spare parts for a range of components with the purchase of a machine. The XX Company is also responsible for replacing parts if the machine breakdowns under normal working condition within the warranty period.

When the new machine is delivered to the customers' plant, XX staff is at the customers site to install and test the machine until it works properly. They also provide customised training services to machine operators depending on the level of their experience and familiarity with the machine. For instance, operation guidance and routine maintenance checklists are part of the training program. This is all included in the machine purchase price.

In contrast, when the machine is outside the warranty period, XX staff offer the same type of phone, e-mail or site services. The on-site support is not offered based on customer request but on whether the support staff feel a site visit is necessary (this may not always be based on a technical necessity but also on the customer perception of being happy with XX) (Table 6.1). For example, customer X called in for technical assistance, XX staff would attempt to solve the problem through e-mail or over the phone. Solutions might be that machine operators were taught how to solve the problem or the appropriate replacement part was posted to customers if they already knew how to repair the breakdown. When the technical problem could not be solved either by e-mail or over the phone, XX staff shall offer a site service. There is no charge for the site visit and the staff time, only repair/replacement parts are charged.

It was noted that the XX Company does not offer spare parts or provide training programmes when the machine is outside its warranty period. Nevertheless, XX staff would help customers to re-install and test the existing machine when customers' companies are relocated.

Due to the limitation of time and schedule, the machines that were purchased and located in China were selected as the focus for this research. The next section will discuss the challenges that the company is facing for providing engineering services.

Table 6.1 Engineering services provided to home and overseas customers

<table>
<tr><th colspan="2">During the One Year Warranty Period</th><th>Engineering Services Charge</th><th>Outside the Warranty Period</th><th>Engineering Services Charge</th></tr>
<tr><td colspan="2">Provide phone or e-mail service based on customer request within 24 hours</td><td>Free</td><td>Provide phone or e-mail service based on customer request within 24 hours</td><td>Free</td></tr>
<tr><td>Provide repair visiting service based on home customer request within 72 hours</td><td>Provide repair visiting service based on overseas customer request within 5 days after obtaining a valid visa</td><td>Free (included maintenance staff, transportation, accommodation, and beverage)</td><td>Provide repair visiting service if HL company considers it is necessary</td><td>Free (included maintenance staff, transportation, accommodation, and beverage)</td></tr>
<tr><td colspan="2">Provide replacement parts necessary to repair the products</td><td>Free (if the machine breakdowns under normal working condition)</td><td>Provide replacement parts necessary to repair the products</td><td>Charge only for reparable parts and postage if necessary</td></tr>
<tr><td colspan="2">Provide spare parts for a range of components</td><td>Free</td><td>Exclusive. Free spare parts are only provided during warranty period</td><td>Not applicable</td></tr>
<tr><td colspan="2">Assign HL staff to install and test the new machine that delivered to customer’s factory</td><td>Free</td><td>Assign HL staff to install and test the existing machine when the customer relocate their factory</td><td>Free</td></tr>
<tr><td colspan="2">Provide customised training course for machine operators</td><td>Free</td><td>Exclusive. Training course are provided when new machines are installed</td><td>Not applicable</td></tr>
</table>

6.2.2 Challenges of the XX Company

From Table 6.1 and the current approach to providing an engineering service the following were identified as the key challenges for XX Company.

As the XX Company provides a series of engineering service without or with little charge to both mainland and overseas customers, it was found that the company has spent a considerable amount of expense on providing this level of service each year. In particular, when the machine is within the warranty period, customers tend to demand as many after-sales service as possible to ensure their machine is working under good condition.

Throughout the years of servicing machines, the company has embedded a proportion of the in-service costs into the selling price of their machine. However, over recent years the company has found that the costs of servicing the machines have continuously reduced the overall profit. The price of the machine is now at the stage that it cannot be increased without the possibility of overpricing and no longer being competitive in the marketplace.

Therefore, to face these challenges, the company is seeking a model to estimate the costs of providing their engineering services, which is the focus of this research. Their aim is to achieve a more profitable contract at the initial purchasing stage of a machine for providing engineering services for the machines. More importantly, they are aiming to offer and deliver an availability or service (i.e., guaranteeing a machine will be available for a set number of hours) contract in the near future. Hence, it is important to understand the activities and costs associated with the in-operation phase of the machines and enable XX Company to estimate the cost of providing such services.

In the next section, how cost related data were collected through the industrial company is presented. A summary and a detailed discussion about the collected data is presented and analysed.

6.3 Data Collection and Analysis

To create an engineering services cost model, it is important to collect and examine reliable and consistent cost data. This section presents a summary of documentary and questionnaire data with critique and analysis. The focus of this section is to illustrate the quality of the data collected and to illustrate the academic rigour applied during the data collection and analysis. This is important as this data is then utilised to create an engineering services cost model which will be described in Chapter 7.

6.3.1 Historical Data Collection and Analysis

Through the research period, the author has worked closely with the industrial partner to collect and analyse historical data. Historical data were collected covering eight years (2003-2010) of data from 78 XX machines. The following table shows a summary of the data collected from XX, including the date, contact person, their role and information about the data.

Table 6.2 Summary of the data collected from the XX Company

Visit	Date	Contact	Position	Data Collection (Data span from 2003 to 2010)
Visit to XX Company	08/02/2010-12/04/2010	Mrs H	Head of Finance	• Information about the machines which were sold from 2003 to 2010 and their corresponding customers
				• Historical engineering services bills spanning the period from 2003-2010
		Mr Y	Head of After-sales Service	• Information related to maintenance staff who worked in XX Company from 2003-2010
				• Historical maintenance record spanning the period from 2003-2010

From Table 6.2 it was not clear where any errors occurred and the researcher wished to ensure that the data was validated and checked. Hence, based on the historical data shown in Table 6.2, an assessment on the quality, validity and reliability of the data was conducted.

a) Quality in Documentary Data

It is known that the quality of the data is dependent on the effective data quality metrics (Pipino et al., 2002). Spasford and Jupp (1996) raised eight questions that are suitable for use when assessing the quality of the documentary data. Kahn and his colleagues (2002) then developed effective data quality dimensions by considering aspects of product quality and service quality. The improved data quality dimensions extend the work of Spasfor and Jupp (1996) by suggesting sixteen dimensions of examining the quality of data. As this research focuses on engineering services, the data quality dimension would be an appropriate and relevant choice for this research.

Taking considerations of the factors listed in their data quality table (Kahn et al., 2002), Tables 6.3 to 6.6 show a summary of the XX Company's data quality by listing the main advantages and drawbacks of the data.

The sixteen factors were used to ascertain the quality of the data. Each of the factors are listed in the left hand column of the tables 6.3-6.6, and the XX data is analysed for each of the quality factors, in terms of advantages, disadvantages. Based on the factors a grading for the quality of XX data, where if the advantages outweigh the disadvantages the data is classified of being adequate or good in terms of its quality.

Table 6.3 A summary of the data quality dimension of the XX Company (Factors 1-4)

Data Quality Factors	**Main advantages of the XX Company's data**	**Main disadvantages of the XX Company's data**	**Conclusions: How good is the XX Company's data quality?**
1. Accessibility: • How easy to access and retrieve data?	• Quick and easy to access and retrieve data from the electronic database • Be able to access the paper documents on site	• Require to learn the company's software to utilise their database • The electronic database is limited to use within the company	• Very good accessibility as the researcher has a personal connection with the XX Company
2. Amount of Information: • Do I have appropriate volume of information to conduct the research?	• Eight years of historical service-related data spanned from 2003-2011 • Eight years of maintenance record spanned from 2003-2011 • Ten experienced maintenance staff conducted a service-related questionnaire (Appendix B)	• Lack of reports for customers who service the machines by themselves	• Very good size and completeness of the information based on the length, breadth and depth of the collected data
3. Completeness: • How complete is the data? • Does the data have sufficient breadth and depth for the research?			
4. Believability: • How true and credible of the data?	• Historical electronic and paper data were collected on site by the researcher herself • Questionnaires were conducted with maintenance on site by the researcher herself • First hand information were collected during visits to customers • Real data were collected through observations, and meeting with staff from the XX Company	• Responses form customers might not have the full credibility as their answers might influence their business with XX Company • Responses from maintenance staff might not have the full credibility as the researcher has a personal connection with the owner of the XX Company	• Moderately true and credible of the data as data were collected through different methods and sources. Moreover, the overall trend seems match with the data collected from different sources

Table 6.4 A summary of the data quality dimension of the XX Company (Factors 5-8)

Data Quality Factors	**Main advantages of the XX Company's data**	**Main disadvantages of the XX Company's data**	**Conclusions: How good is the XX Company's data quality?**
5. Concise Representation: • Does the data compactly represented?	• The selected company is a typical medium size manufacturing and service supplier in China • Although the data were collected based on a single case study, the breadth and depth of the data was considerably large	• The industrial data collected was from a single manufacturing company	• Data may not be represented for different scenarios of manufacturing service suppliers, however, the approach and framework for estimating the costs of providing such service might adapt to other cases.
6. Consistent Representation: • Does the data presented in the same format?	• Most of the cost data were stored electronically • Most of the maintenance record were stored electronically • Responses of all questionnaires were presented in a word document.	• Some of the old service-related data were presented on papers	• In general, good consistent representations of historical data. However, a few missing electronic data were found on paper documents.
7. Ease of Manipulation: • How easy to manipulate and apply to different scenarios?	• The data was collected consistently by the same researcher • The data was analysed and presented in the same format	• Time-consuming and tedious to extract and re-arrange the appropriate data from the database for different tests • Require to learn the XX company's internal software in order to manipulate the data	• Moderately hard and time-consuming to manipulate the data as the database is complex and lacks of flexibility
8. Free of Error: • How correct and reliable of the data?	• The data was collected directly by the researcher on site so mistakes were avoided from a third party • The data were checked and examined by the researcher on site so any missing/incorrect data were clarified by the appropriated XX staff	• Time-consuming and tedious to check and examine a large amount of data • Require time and effort from appropriated staff who recorded or familiarised with the data	• As far as the researcher's concern, the data was correct and reliable. Because the researcher has examined the data with internal staff and ensure the centres data would be the total of the sub-data from different departments.

Table 6.5 A summary of the data quality dimension of the XX Company (Factors 9-12)

Data Quality Factors	Main advantages of the XX Company's data	Main disadvantages of the XX Company's data	Conclusions: How good is the XX Company's data quality?
9. Interpretability: • To what extent that the information is in appropriate languages, symbols and units, and the definitions are clear?	• All the cost-related data were presented in Chinese currency. Thus, the service cost model would be created based on Chinese units to avoid the inaccuracy of currency exchange. • Although all the service-related data were originally presented in Chinese, the researcher is fluent in both Chinese and English. Thus, the accuracy of the translation seems reasonable. • The researcher would check the translated data with appropriate language experts to avoid misinterpretation.	• Time-consuming to translate a large amount of data between Chinese and English • Misunderstanding or confusions might occur due to the culture or language differences	• Interpretability is good in this case as the researcher is a native Chinese speaker who has studied in the UK for nearly ten years • The accuracy of the translated data were improved by double checking with language experts
10. Objectivity: • How unbiased, unprejudiced , and impartial of the data?	• Service-related data spanned from 2003-2011 covering 78 machines, with each has a equal chance to be selected and tested	• The researcher had no control to the original source of the data • Data were recorded by different staff at different years	• The collected data was generally objective despite from the potential human errors
11. Relevancy: • How applicable and helpful for the research?	• The service-related costs were thoroughly examined for the XX machines	• The data was collected from one machine and service provider, so itself may not represent to other cases	• Although the data may not represent in different industries, the depth and breadth of the data provide a good insight for this research
12. Reputation: • Is the data highly regarded in terms to its source or content?	• The selected case study company was a leading company in providing products and services for a particular industry in China	• The data were collected from a private firm • There were hardly any well-known public sources	• Good reputation as real data was collected from the leading machine and service provider in China

Table 6.6 A summary of the data quality dimension of the XX Company (Factors 13-16)

Data Quality Factors	Main advantages of the XX Company's data	Main disadvantages of the XX Company's data	Conclusions: How good is the XX Company's data quality?
13. Security: • To what extent that the data is restricted appropriately to maintain its security?	e) The cost-related data was restricted to appropriated managers within the XX Company	f) Competitors or experts might have a general idea about the service-related costs.	g) High security as the service-related data was confidential among the top mangers within the company
14. Timeliness: • To what extent that the data is sufficiently up-to-date for the research?	h) The collected data were updated three times during the visits	i) The data can only be updated internally within the XX Company	j) The data is up-to-date as it spanned from 2003-2011
15. Understandability: • To what extent that the data is easily comprehend-ed?	k) The researcher has immerse herself within the company to collect and examine the data l) Working closely with XX staff, some data were clarified clearly	m) There are a few cases that the information was not clearly clarified as the person who recorded the data have left the company	n) The data used to develop the cost model was fully understood o) The unclear data was withdrawn from the test to minimise uncertainty
16. Value-Added: • To what extent that the data is beneficial and provides advantages from its use?	• A full set of cost-related data were collected, which were often private and confidential	• Not applicable	• The data used to create an engineering services cost model which currently is a gap in literature and a challenge in industry

As depicted in Tables 6.3 to 6.6, the quality of the collected data was analysed from sixteen different dimensions. The findings showed that the overall quality of the collected data was acceptable and reliable for conducting this research.

b) Validity in Documentary Data

By answering the 16 questions the data was found to be relevant to this research as it provided cost-related data, which was the focus of this research. The data was checked and updated three times to ensure accuracy. The overall cost was examined by adding up the sub-costs from different departments. Furthermore, the quantitative data was recorded in appropriate figures, whereas, the qualitative data was generally recorded in a clear and consistent manner. Finance and after-sales service staff justified missing or misinterpreted data. Hence, the precision of the data was satisfactory for this research. The relevance, accuracy and precision of the data seemed to be acceptable, which met the three criteria for validity (Sarantakos, 2005).

c) Reliability in Documentary Data

Tables 6.3 to 6.6 considered the reliability of the data, which was one of the key factors to measure the quality of data. Reliability indicated the capacity of measurement to produce consistent results that could be repeated by following the same procedure, and was free of bias with the researcher and the respondents (Sarantakos, 2005). In this particular case the service-related data was stored either in the electronic database or on hard copy hence it would not be affected by either the researcher or the bookkeeper. Moreover, in terms of quantitative data, adding up the sub-costs from different divisions checked the overall costs. In terms of qualitative data, it was checked and justified by appropriate staff. More importantly, checking and updating the data three times before developing a service cost model examined the reliability of the data. Hence, the documentary data seemed to be reliable which meant applying the same procedures could produce the same results.

6.3.2 XX Maintenance Staff Questionnaire

Within this section, the background and methods of conducting the maintenance staff questionnaire is introduced. A general discussion and analysis about the outcomes of this research are also presented. The information in Table 6.7 shows the general background of the maintenance staff questionnaire used in this research. It includes questionnaire information related to the date, duration, place, conductor, target and purpose.

Table 6.7 Summary of the data collected from the XX Company

Questionnaire Completion Date	10/02/2010-09/03/2010
Questionnaire Duration	Approximately thirty days for completing Questionnaire 1
Questionnaire Place	The After-sales Service Department of XX Company
Questionnaire Conductor	The PhD researcher
Questionnaire Target	XX maintenance staff who was responsible for providing engineering service to customers
Questionnaire Purpose	• To fill in the gaps of documentary data collected from the XX Company • To identify how the engineering services are offered by XX staff

Questionnaire Method:

A Questionnaire was designed and conducted by XX maintenance staff (Appendix B). The questionnaire was written in English initially and translated into Chinese for respondents. The questionnaire was prepared in a word document, and it was then printed in hard copy and handed to each XX maintenance staff separately at different times. This was because a certain number of XX maintenance staff were usually undertaking on-site services to different customers. Therefore, it was common that not all the maintenance staff were available in the company simultaneously. In addition, they were told to fill in the questionnaire based on their own experience rather than from the historical records. The deadline of the questionnaire was then given to each respondent. As the researcher was based in the company while conducting the questionnaire, the completed questionnaire was handed in as soon as it was finished. Moreover, during the completion period, maintenance staff were guided not to discuss the questionnaire or compare their results with each other. Meanwhile, the researcher had no conversations with maintenance staff regarding the questionnaire.

Questionnaire Outcome:

There were nine maintenance staff that had five to fifteen years experience of servicing the XX machines. One was the head of the After-sales Service Department, four mechanical maintenance staff and four electrical maintenance staff.

Based on Questions 1-6, the background of XX maintenance staff and their views on different types of maintenance service were discovered. Most of the maintenance staff suggested that the XX Company were mainly offering corrective maintenance service. Although they provided some preventative maintenance service to customers which were near to the place of their on-site corrective maintenance visits, preventative maintenance was offered randomly and XX Company did not have clear historical records. In addition, each maintenance staff was responsible for approximately five on-site repair services.

Based on Question 7, machine breakdown parts and the reasons for failure were discovered. The maintenance staff suggested that most of the common failure parts were non-repairable. They failed due to different types of reasons, such as work overload, work under high temperature, design/assembly problems.

Based on Questions 8-12, XX maintenance staff's opinions on phone service and on-site repair service were found. Most of the maintenance staff suggested that around 80% of the engineering service was on-site service, whereas 20% was phone service. In addition, approximately 80% of the maintenance staff on-site working hours were spent on providing repair service. They also recommended that some of the on-site repair problems could be solved over the phone, hence more phone service should be offered in the future.

From Question 13, when a new machine was delivered to the customers' plant, maintenance staff provided customised training service to machine operators depending on the level of their experience and familiarity with the machine. For example, operation guidance and routine maintenance checklists were included in the training program. This was all included in the machine purchase price.

Question 14 was incomplete as maintenance staff were not familiar with the concept of engineering service contracts and did not know the costs for providing engineering services.

From the data collection the historical data was verified as suitable.

6.4 Summary

This first part of this chapter discussed the reasons for selecting the XX Company as a basis for achieving the aim of this research, listing advantages and disadvantages of applying a single case study method. The background of the case study company was briefly introduced and a discussion on the types of engineering services offered by the company provided was presented. Challenges that the company is facing and the reasons that they want to estimate the cost of engineering services were also described.

The second part of this chapter presented a summary of documentary and questionnaire data with critique and analysis. In particular, the quality, validity and reliability of the data were examined to illustrate the academic rigour. Moreover, the maintenance staff questionnaire was used to fill in the gaps of documentary data, and identify how XX staff provides engineering services.

The findings from the data gathering showed that there were three categories of engineering services offered by the XX Company, namely: phone, spare parts or on-site repair.

In the next chapter, an engineering services cost model is created based on the data collected from the case study company for these three levels of engineering services.

Chapter 7 The Engineering Services Cost Model

This chapter discusses how the engineering services cost model was created by following step 2 of the approach (Chapter 5: Figure 5.1). The scope and process of the engineering services cost modelling are introduced. Assumptions and notations for the model are then presented. The focus of the cost model presented in this chapter is on how to identify performance factors and Cost Estimating Relationships (CERs), i.e. the parametrics for estimating the cost of providing phone service, spare parts service and on-site repair service. The data utilised is from Chapter 6.

7.1 The scope and process of the engineering services cost modelling

The aim of the engineering services cost model was to predict the future costs of providing engineering services for the XX Company. The company mainly offers three types of engineering services, namely; phone service, spare parts service and on-site repair service. The process of providing these services to their customers is presented in Figure 7.1. Figure 7.1 depicts the actions that occur when a problem is encountered on a customer's machine. As depicted in Figure 7.1, the normal process is that when the problem related to the machine occurs, the operator at the customer site normally telephones the XX maintenance staff for assistance. Based on the customer's request, maintenance staff initially provide over the phone service. During the telephone discussion problems might be identified and service solutions could be suggested. When the phone service is completed, there are generally three possibilities.

1. Based on maintenance staff advice, customers sometimes were able to solve the problem by themselves.
2. If the problem was identified and could be resolved by replacing a spare part, the spare part service was provided. Once this service was provided, customers might replace the spare part and hence fix the technical problem by themselves.
3. If the problem was not identified or the problem was identified but the customers did not know how to replace a spare part or fix the problem, an on-site service was offered.

In general, the XX Company offered these three types of engineering services in this order, with the priority being to try and have the customer solve the problem by themselves after advice from XX maintenance staff.

Using the activities identified in Figure 7.1, the scope of the engineering services cost model was defined. This means that the costing scope of this model was to estimate the costs of phone service, spare part service and on-site repair service. More importantly, the modelling process of the cost model is based on the general process of XX Company that provides their engineering services (Figure 7.1).

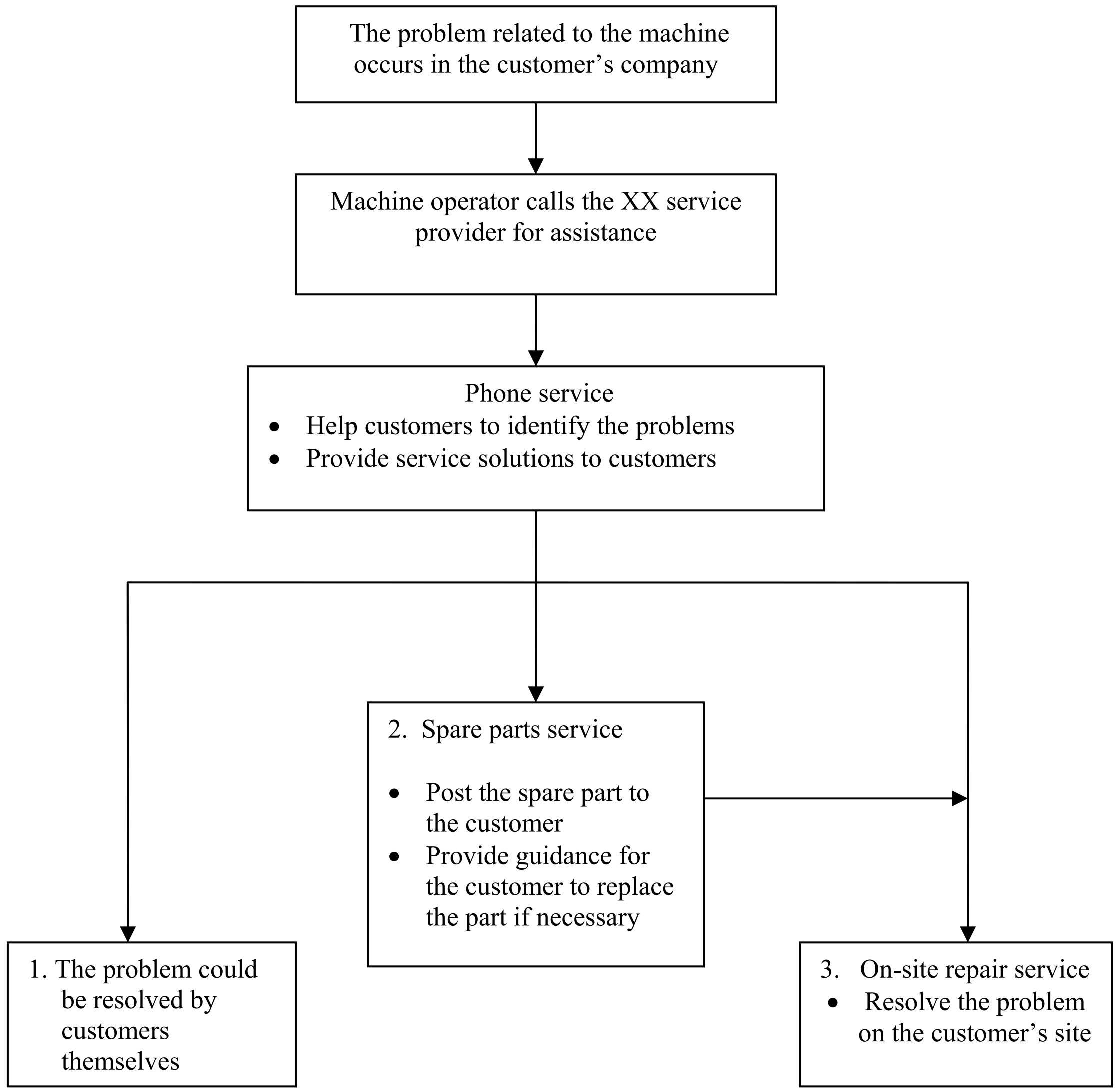

Figure 7.1 The general process for XX Company to provide engineering services

7.2 Creation of the Cost of Engineering Services Model

The engineering service cost model was created based on the data collected in Chapter 6. There were 78 machines from the same XX production line sold during 2003-2010. These 78 machines were all based at different customer sites, i.e. 78 different customers as 1 machine was sold to each customer. All of the customer sites were located in Mainland China.

To create an engineering services cost model it was necessary to identify the performance factors and CERs that may influence the cost of providing such a service. These utilise the information and findings from the data analysis presented in Chapter 6. Meanwhile, for the cost estimation model, it was necessary to define the notation and assumptions for these variables. The following lists the notations and assumptions. Based on these the engineering services cost model was then created.

7.2.1 Notations

The following quantities are defined for use in the model and analysis that follows:

I_s	=	the year the machine is sold (and enters engineering service)
i	=	years in operation
j	=	year of operation
N_{si}	=	number of machines sold that year
N_{ij}	=	the number of failures of machines in operation for at least i years during their j^{th} year of service
N'_{fj}	=	Actual total number of failures in the j^{th} year of operation
N_{fj}	=	Total expected number of failures in the j^{th} year of operation
λ'_j	=	Actual machine failure rate in the j^{th} year of operation
λ_j	=	Expected machine failure rate in the j^{th} year of operation service
N_i	=	the total number of machines in operation for at least i years
N_s	=	the total number of machines sold in year Is
N_{is}	=	the total number of machines in operation in their Is year
N_{ep}	=	the total number of expected phone calls in the Is year
N_p	=	the total number of phone service provided in the Is year
N_m	=	the total number of maintenance staff in the Is year

C_{lj}	=	Total labour costs for machines in the *Is* year
C_{lj_p}	=	Total labour costs for providing phone service in the *Is* year
C_{lj_v}	=	Total labour costs for providing on-site repair service in the *Is* year
C_{tpj}	=	Total transportation costs for machines in the *Is* year
C_{aj}	=	Total accommodation costs for machines in the *Is* year
C_{mj}	=	Total meal costs for machines in the *Is* year
C_{pj}	=	Total phone service costs for machines in the *Is* year
C_{pmj}	=	the average phone cost per machine in the *Is* year
C_{sp}	=	Total costs for spare parts for machines in the *Is* year
C_{po}	=	Total costs of postage for delivering spare parts for machines in the *Is* year
C_{st}	=	Total costs of storage all spare parts in XX in the *Is* year
C_{st_used}	=	The costs of storage used parts in the *Is* year
C_{sps}	=	Total costs of providing spare part service in the *Is* year
C_{sps_m}	=	Total costs of providing spare part service per failure in the *Is* year
C_{sj}	=	Total subsidies for travelling for machines in the *Is* year
C_{boj}	=	Total bonus for providing a good engineering service for machines in the *Is* year
$C_{average\_6j}$	=	the average C_{6j} service cost per failure in the *Is* year
C_{6j}	=	total costs for C_{tpj}, C_{aj}, C_{mj}, C_{sj}, C_{lj_v},& C_{boj} in the *Is* year
$C_{average\_lj}$	=	the average costs of maintenance staff in the *Is* year
$C_{average\_pj}$	=	the average costs of providing a single phone service in the *Is* year
CER_1	=	Expected total phone costs in the j^{th} year of operation
CER_2	=	Expected total spare part costs in the j^{th} year of operation
CER_3	=	Expected total on-site repair service costs in the j^{th} year of operation
C_{es}	=	Expected total engineering service costs in the j^{th} year of operation

7.2.2 Assumptions

The cost model was created based on several assumptions. These include:

1. All machines are identical in terms of components and are sourced from the same supplier.
2. All machines have the same operating conditions, despite being introduced into service in different years.
3. All machine failures are repairable by replacing the non-repairable parts.

4. All costs are in Chinese Currency, which is RMB. This assumption was to enable the researcher to feedback the findings to the machine and service provider. The currency would need to be adjusted as well as the staff costs for particular countries.

The manufacturer and service provider confirmed that the assumptions were reasonable, although the author acknowledges that there may be a need in future research to weight the customer site operating conditions when estimating the cost of engineering services. This would account for any misuse or overloading of the machines.

7.2.3 Engineering Services Cost Modelling

The aim of the cost model was to estimate the cost of providing engineering services to XX customers. The categories of engineering services used in this thesis includes phone services, spare parts services, and on-site repair services. Therefore, this model includes the cost incurred at the in-operation stage of providing these engineering services. The following sections describe how to create the cost model by identifying two performance factors and four CERs.

a) Identify performance factors:

In total there were 78 machines from the same production line sold during 2003-2010. Customers purchased these new machines during different years, so they have different numbers of in-operation years during the eight-year period studied. The number of machines sold and the number of machine failures occurring during the 2003-2010 period are summarised in Table 7.1.

Table 7.1 The Number of Machines Sold and the Number of Failures Recorded

Year sold to customers (I_s)	*Years in operation (i)*	*Number of machines sold that year (Ns_i)*	*Number of Machine Failures (N_{ij})*							
			1st year in operation (j = 1)	**2nd year in operation (j = 2)**	**3rd year in operation (j = 3)**	**4th year in operation (j = 4)**	**5th year in operation (j = 5)**	**6th year in operation (j = 6)**	**7th year in operation (j = 7)**	**8th year in opreration (j = 8)**
2003	1	8	4	1	1	3	1	0	1	0
2004	2	15	16	15	2	2	1	2	0	-
2005	3	9	15	11	3	9	1	1	-	-
2006	4	9	14	9	23	12	2	-	-	-
2007	5	6	23	4	6	3	-	-	-	-
2008	6	11	22	11	4	-	-	-	-	-
2009	7	9	31	17	-	-	-	-	-	-
2010	8	11	37	-	-	-	-	-	-	-

Table 7.1 shows that eight machines were sold in 2003 and by the end of 2010 had been in operation for eight years, fifteen machines were sold in 2004 that had seven in- operation years as of 2010 and so on. The eight machines sold in 2003 had a total of four failures during their first year in-operation, and this reduced to one failure in their second and third year of operation. The failure rate increased to three in the fourth year, and so on.

Based on Table 7.1, the total number of machines and total number of machine failures are presented in Table 7.2. It shows that there are 78 machines in-operation for at least one year, 67 out of 78 were in operation for at least two years, and so on. Furthermore, the 78 machines had 162 combined failures in their first operation year, 67 machines had 68 failures in the second operation year, and so on. Each machine could fail more than once or not at all during an operation year. Of the machines that failed during the first year, the repaired machines could fail again in subsequent years. For example, the 67 failures occurring during the second year includes machines that failed in the first year, were repaired, and failed again in their second year in operation.

The machine failure rate is calculated as a ratio of the total number of failures divided by the total number of machines in operation for at least *i* years. This relationship calculated between the machine failure rate and the number of years in operation is shown in the last column of Table 7.2.

Based on Table 7.2, the failure rates are shown as a dashed line in Figure 7.2. A 208% failure rate occurred on 78 machines during their first year in-operation, which means that on average, every machine had around 2-3 failures during its first year in operation. However, in year two this reduced significantly to ~101% based on a sample of 67 machines. During the third and fourth in-operation years, the machines failed less frequently. After machines had been in operation for more than four years, the failure rates reduced significantly to less than 15%. In general, within the eight in-operation years, the longer the machine had been in operation, the less likely it was to fail. This particular trend fits the characteristics of the exponential distribution (Das, 2008; Ahsanullah and Hamedani, 2010; NIST/SEMATECH, 2012). As the exponential distribution is a common approach to model the machine failure (Maillart

& Pollock, 1999; Diallo et al., 2001; Das, 2008; Murphy, 2012), it is selected as the basis of modelling the failure rate for the XX machines.

Table 7.2 Number of Machines in Operation for at Least i Years; Number of Failures and Failure Rate in the jth Year of Operation

Years in operation (i)	***Number of machines in operation for at least i years (N_i)***	***Year of operation (j)***	***Number of failures in the j^{th} year of operation (N_{f_j})***	***Machine failure rate in the j^{th} year of operation*** $(\lambda'_j = N_{f_j}/N_i)$
1	$\sum_{i=1}^{8} N_{s_i} = 78$	1	$\sum_{i=1}^{8} N_{i1} = 162$	208%
2	$\sum_{i=1}^{7} N_{s_i} = 67$	2	$\sum_{i=1}^{7} N_{i2} = 68$	101%
3	$\sum_{i=1}^{6} N_{s_i} = 58$	3	$\sum_{i=1}^{6} N_{i3} = 39$	67%
4	$\sum_{i=1}^{5} N_{s_i} = 47$	4	$\sum_{i=1}^{5} N_{i4} = 29$	62%
5	$\sum_{i=1}^{4} N_{s_i} = 41$	5	$\sum_{i=1}^{4} N_{i5} = 5$	12%
6	$\sum_{i=1}^{3} N_{s_i} = 32$	6	$\sum_{i=1}^{3} N_{i6} = 3$	9%
7	$\sum_{i=1}^{2} N_{s_i} = 23$	7	$\sum_{i=1}^{2} N_{i7} = 1$	4%
8	$\sum_{i=1}^{1} N_{s_i} = 8$	8	$\sum_{i=1}^{1} N_{i8} = 0$	0%

However, the data did not demonstrate a bathtub failure model but only represented the initial stages of the bathtub failure, i.e. early failures leading to the useful life. As stated in the previous paragraph this is representative of the exponential distribution. So the historical data demonstrated that the move from early failures to useful life occurred around the fourth year of the machines being in operation.

For the machine failure data from 2003-2010, an exponential trend curve was plotted in Figure 7.2. It was also found that the correlation and correlation coefficient between the number of years in-operation and the machine failure rate are $\lambda_j = 4.1382e^{-0.6269j}$ and 0.9653, where λ_j represented expected machine failure rate and j indicated the number of years in-operation. This relationship is defined as Equation 7.1.

$$\lambda_j = 4.1382e^{-0.6269j} \qquad \text{(Equation 7.1)}$$

In general, as the correlation coefficient becomes closer to 1, the established relationship is more valid and reliable (Huang et al., 2011). Hence, the correlation coefficient of 0.9653 shows that there was a strong correlation between the expected machine failure rate and the number of years in operation for the XX machines.

Moreover, the expected number of machine failures in the j^th^ year (N_{f_j}) is calculated by multiplying the expected machine failure rate in the j^th^ year (λ_j) multiplying the number of in-operation machines in the j^th^ year (Equation 7.2). This relationship is established as Equation 7.2.

$$N_{f_j} = \lambda_j \times N_j = 4.1382\, e^{-0.6269\, j} \times N_j \qquad \text{(Equation 7.2)}$$

This becomes useful when estimating the cost of providing engineering services for the XX customers as the length of the contract and the life phase of the machine will influence the engineering services cost (Chapter 9).

Figure 7.2 The relationship between machine failure rate and years in-operation (1-8yrs)

b) <u>*Identify CERs:*</u>

This section defines four key CERs for providing engineering services to the XX customers. The engineering services include phone service, spare parts service and on-site repair service.

1) Define the CER for providing phone service.

While receiving phones calls from customers, the XX maintenance staff aim to provide a response within 24 hours. This type of engineering services is the phone service. The service is provided throughout the service contract life of each machine.

Although there was no historical data about the number of phone service recorded, there was a record on the number of machine failures during 2003-2010.

As mentioned earlier, the on-site repair service was generally provided only when the technical problem could not be resolved over the phone. Therefore, it seems reasonable to create Assumption (1):
The number of phone service were equal or greater than the number of on-site repair service provided to customers during 2003-2010

Hence, the number of on-site repair service (N_{fi}) collected from the XX Company is presented in Table 7.3. As the XX Company defines the machine failures that are failures being repaired on the customer's site, the number of machine failures in the I_s year is equal to the number of on-site repair service in that year. From Table 7.3, there were 8 machines sold in 2003, 15 machines sold in 2004, 9 machines sold in 2005 and so on. Furthermore, the 8 machines had one on-site repair service in 2003, four on-site repair service in 2004, and so on.

Table 7.3 The Number of Machines Sold and the Number of On-site Repairs Recorded

Year sold to customer (I_s)	***Number of machines sold that year (N_{s_i})***	***Number of On-site Repairs = Number of machine failures* in the *Is* year (N_{fi})**							
		2003 (Jan.-Dec.)	**2004 (Jan.-Dec.)**	**2005 (Jan. -Dec.)**	**2006 (Jan. -Dec.)**	**2007 (Jan. -Dec.)**	**2008 (Jan. -Dec.)**	**2009 (Jan. -Dec.)**	**2010 (Jan.-Dec.)**
2003	8	1	4	1	1	3	0	0	1
2004	15	-	7	20	4	3	1	2	0
2005	9	-	-	12	9	6	3	8	1
2006	9	-	-	-	8	12	13	24	4
2007	6	-	-	-	-	6	20	8	3
2008	11	-	-	-	-	-	8	22	4
2009	9	-	-	-	-	-	-	15	23
2010	11	-	-	-	-	-	-	-	13

Based on Tables 7.3, the total number of on-site repair service is calculated and presented in Table 7.4. For example, the number of on-site repair service provided in

2004 is calculated as the sum of the total number of on-site repair service provided for machines sold in 2003 in their second operation year added to the total number of on-site repair service provided for machines sold in 2004 in their first operation year (i.e. 4+7) and so on. Based on Assumption (1), the values (N_{is}) presented in Table 7.4 could also act as the minimum number of phone service during 2003-2010.

Table 7.4 Number of On-site Repair Service for Machines in there Is Years

Year sold to customer (Is)	***Total Number of machine failures* in the *Is* year *(N_{is})***
2003	1
2004	11
2005	33
2006	22
2007	30
2008	45
2009	79
2010	49

Based on past experience, the XX Company assumed that the number of maintenance staff was hired based on the expected number of machine failures, whereas the number of on-site repair service was dependent on the actual number of machine failures. The XX Company also assumed that each maintenance staff was able to handle five on-site repair visits each year (Chapter 6). Based on assumption (1), each maintenance staff would at least be able to handle five phone calls. These values are presented in Table 7.5.

As the costs of XX maintenance staff to provide phone service was embedded in their salary, there were no separate costs identified for the provision of telephone service. However, based on the maintenance staff questionnaire (Chapter 6), it was discovered that around 20% of the maintenance staff time was spent on providing phone service. Hence, the cost of maintenance staff providing a phone service (Clj_p) is calculated as the product of total costs of maintenance staff (C_{lj}) multiplied by 20%. This is also presented in Table 7.5.

Table 7.5 Maintenance staff in the Is Year

Year sold to customer *(Is)*	Number of expected phone calls (N_{ep})	Number of Maintenance Staff (N_m)	Average cost per maintenance staff (Caverage_lj)	Total Maintenance Staff Salary (Clj)	Maintenance Staff Costs (Clj_p= Clj*20%)
2003	20	4	22,636	90545	18109
2004	25	5	26,000	130000	26000
2005	35	7	20,400	142800	28560
2006	40	8	22,500	180000	36000
2007	45	9	25,556	230000	46000
2008	45	9	26,667	240000	48000
2009	50	10	27,000	270000	54000
2010	55	11	29,091	320000	64000

The total phone costs incurred at the in-operation stage (year 2003 to 2010) of providing engineering services collected from the industrial company is tabulated in Table 7.6. The total phone costs (Cpj) include the costs of providing phone line (Cplj) and the costs of maintenance staff (Clj_p).

Table 7.6 Total cost of Phone Service in the Is Year

Year sold to customer *(Is)*	Phone Line (Cplj)	Maintenance Staff Costs (Clj_p= Clj*20%)	Total Telephone Service Costs (Cpj= Cplj+ Clj_p)
2003	5,000	18,109	23,109
2004	8,000	26,000	34,000
2005	12,600	28,560	41,160
2006	16,000	36,000	52,000
2007	27,000	46,000	73,000
2008	30,000	48,000	78,,000
2009	30,000	54,000	84,000
2010	38,000	64,000	102,000

Based on the results summarised in Tables 7.5 and 7.6, the average phone cost per failure ($C_{average\_pj}$) during 2003-2010 was calculated. Based on Assumption (1), C_{pmj} is calculated as a ratio of the total cost of phone service (C_{pj}) divided by the total number of on-site repair service (N_{is}) at the *Is* year. The costs are presented in Table 7.7.

Table 7.7 Average phone cost per failure in the Is Year

I_s	***Total number of machine failures in the I_s year (N_{is})***	***Average phone cost per failure*** **($C_{average\_pj} = C_{pj} / N_{is}$)**
2003	1	23,109
2004	11	3,091
2005	33	1,247
2006	22	2,364
2007	30	2,433
2008	45	1,733
2009	79	1,063
2010	49	2,082

The average phone cost per failure and the corresponding in-operation years are shown in Figure 7.3. The results show that the average phone cost per failure ($C_{average\_pj}$) fluctuated during 2003-2010. When the number of phone services increased significantly from 1 to 11 in 2003 and 2004 respectively, the average cost of providing a single phone service dropped by nearly 87%. Similarly, when the number of phone services decreased slightly from 33 to 22 in 2005 and 2006, the cost for providing such service also increased by 90% from RMB 1247 to RMB 2364 approximately. In contrast, since 2006 the number of phone services continued to increase, the costs of providing a single phone service increased, decreased and increased again.

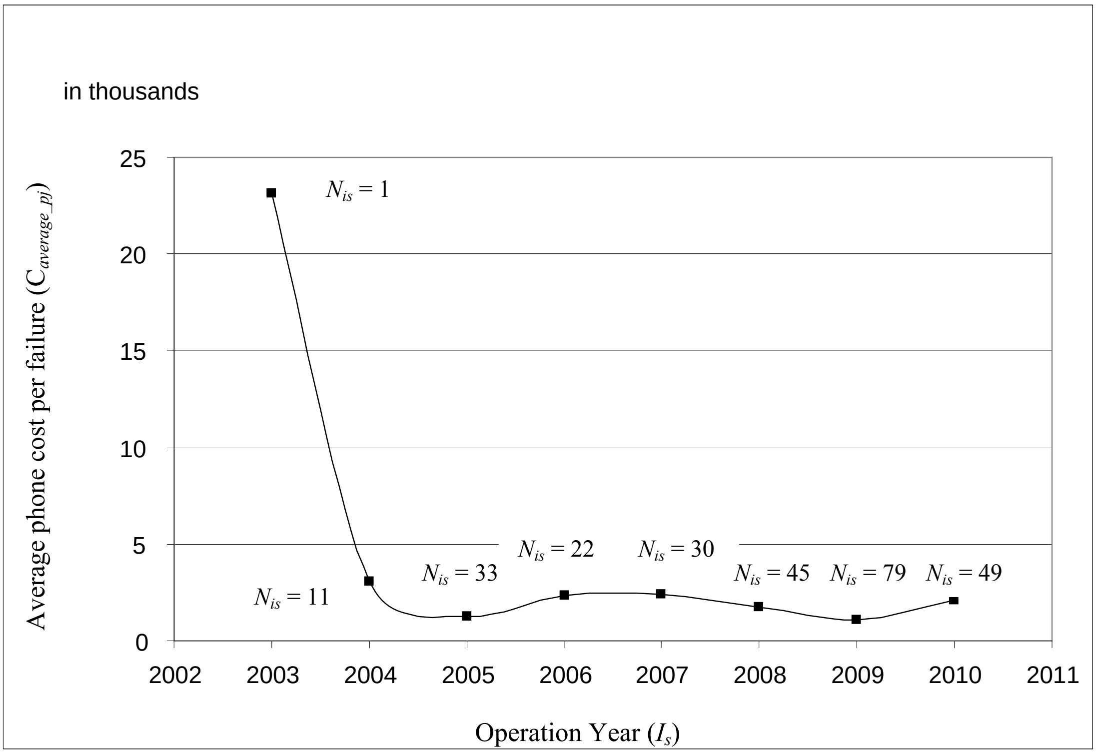

Figure 7.3 The relationship between average phone cost per failure and the operation year

The following section describes the reasons that the phone service data from 2003 was excluded from the engineering services cost model. The average phone cost per failure and its fluctuated range are then estimated. The CER for estimating the total phone service costs for different numbers of machines is defined.

The average phone cost per failure ($C_{average\_pj}$) in 2003 was RMB 23,109, which was much higher than the cost for phone service for the machines during the rest of the in-operation years. 2003 was highlighted as a special case for three important reasons: First, there were a number of changes within the XX Company in 2003. The company restructured and expanded to a private Limited Corporation. Existing machines were redesigned and upgraded and new maintenance staff were hired. As the maintenance staff were less familiar and had less experience with the XX machines in 2003 than the rest of the machine service years, the duration and number of phone service they provided in that year were likely to be longer and more frequent.

Second, the 78 machines investigated belonged to the new production line, which was set up in 2003. Therefore the design and manufacturing method of the new product may not be mature and could have hidden faults causing problems. Therefore, the number of phone service was probably higher in the first in-operation year of the machine than the rest of the years.

Third, the customers hardly had any experience with the new design of the machine; hence XX Company probably offered phone service frequently to provide guidance and support for the machine operators in 2003.

Based on these three reasons, it was considered necessary to exclude the average phone cost per failure that occurred in 2003 from the engineering services cost model as the cost data occurred under different conditions.

To define the CER for providing phone service, the average phone cost per failure should be estimated. Excluding the data from 2003, Figure 7.3 shows that the average phone cost per failure varied between RMB 1063 and RMB 3091 during 2004-2010.

Based on Table 7.7, the average phone cost per failure is estimated as approximately RMB 2002. This is calculated as the sum of average phone cost per failure ($C_{average\_pj}$) occurring during 2004-2010 divided by 7 (Equation 7.3).

CER_1 is defined as the cost estimating relationship for predicting the total cost of providing phone service during seven in-operation years. The relationship between the total phone service cost (CER_1) and the number of years in operation (j) was determined from Equation 7.3 and Equation 7.2 respectively. The phone service costs (CER_1) are estimated by multiplying the average phone cost per failure ($C_{average\_pj}$) by the number of predicted failures that occurred in the j^{th} year. CER_1 is established as Equation 7.4:

CER_1 = average phone cost per failure x expected number of machine failures in the j^{th} year

$$= 2002 \times N_{f_j}$$

$$= 2002 \times 4.1382\, e^{-0.6269\, j} \times N_j \qquad \text{(Equation 7.4)}$$

2) Define the CER for providing spare parts service.

When the machine breakdowns occurred, the operator recorded the failure time and phoned the XX service provider to repair the machine. If the problem could be resolved by replacing a spare part, the service provider usually sent the part to the customer through post. This type of engineering services is called the spare parts service.

The spare parts service is offered to the set of machines presented in Table 7.3 throughout the engineering service contract life of each machine. The costs incurred at the in-operation stage (year 2003-2010) of providing spare parts services includes the costs of used spare parts, postage and storage. The total cost of spare parts (Csp), the costs of postage (Cpo), and the total storage costs of all spare parts (Cst) collected from the XX Company is tabulated in Table 7.8.

It was discovered that the total storage costs of used spare parts is calculated as the product of the total storage costs of all spare parts multiplied by approximately 7.5% of inventory falling price reserves in the XX Company. The inventory falling price reserves indicated existing stock that was damaged, aged, outdated and could not be used in the coming years. The XX Company used this value as stock depreciation to estimate the costs of storage for used spare parts. Hence, the storage costs of used spare parts (Cst_used) were calculated in Table 7.8.

Moreover, the total cost of providing spare part service annually (Csps) is calculated as the sum of the costs of used spare parts, postage and storage. This value is also presented in Table 7.8. It was discovered that the replacement parts requested were normally non-standardised, i.e. they were specifically designed for XX machines.

Table 7.8 Total Spare Part Service Cost Variables;
Total Costs for providing Spare Part Service (years 2003-2010)

Year sold to customer (Is)	***Total cost of spare parts and postage*** **(Csp + Cpo)**	***Total storage costs of spare parts*** **(Cst)**	***Total storage costs of used spare parts*** **(Cst_used= Cstx7.5%)**	***Total cost of providing spare part service*** **(Csps= Csp + Cpo+ Cst_used)**
2003	260,000	4,000,000	300,000	560,000
2004	285,000	4,880,000	366,000	651,000
2005	300,000	8,300,000	622,500	922,500
2006	380,000	10,250,000	768,750	1,148,750
2007	500,000	12,600,000	945,000	1,445,000
2008	560,000	10,420,000	781,500	1,341,500
2009	700,000	12,900,000	967,500	1,667,500
2010	800,000	15,000,000	1,125,000	1,925,000

The XX maintenance staff provided spare part service to the same groups of machines presented in Table 7.3. From Table 7.9, the average cost of spare part service per machine (Csps_m) is calculated as the quotient of total costs of providing spare part service (Csps) divided by the corresponding total number of failures (N_{is}).

Table 7.9 Average Spare Part cost per failure in the Is year

Year sold to customer (I_s)	***Total number of machine failures in the I_s year (N_{is})***	***Average spare part cost per failure*** **(Csps_m= Csps/ N_{is})**
2003	1	560,000
2004	11	59,182
2005	33	27,955
2006	22	52,216
2007	30	48,167
2008	45	29,811
2009	79	21,108
2010	49	39,286

The average spare part costs per failure and the corresponding in-operation years are shown in Figure 7.4. It demonstrates that the average spare part cost per failure (Csps_m) fluctuated during 2003-2010. When the number of in-operation machines increased significantly from 1 to 11 in 2003 and 2004 respectively, the average cost of providing spare parts service per machine dropped by nearly 89%. The first year of providing spare parts service per failure (2003) was much more costly than providing such a service for the rest of the operation years (2004-2010). More importantly, since 2004 as the number of in-operation machines continued to increase each year, the costs of providing spare parts service changed slightly.

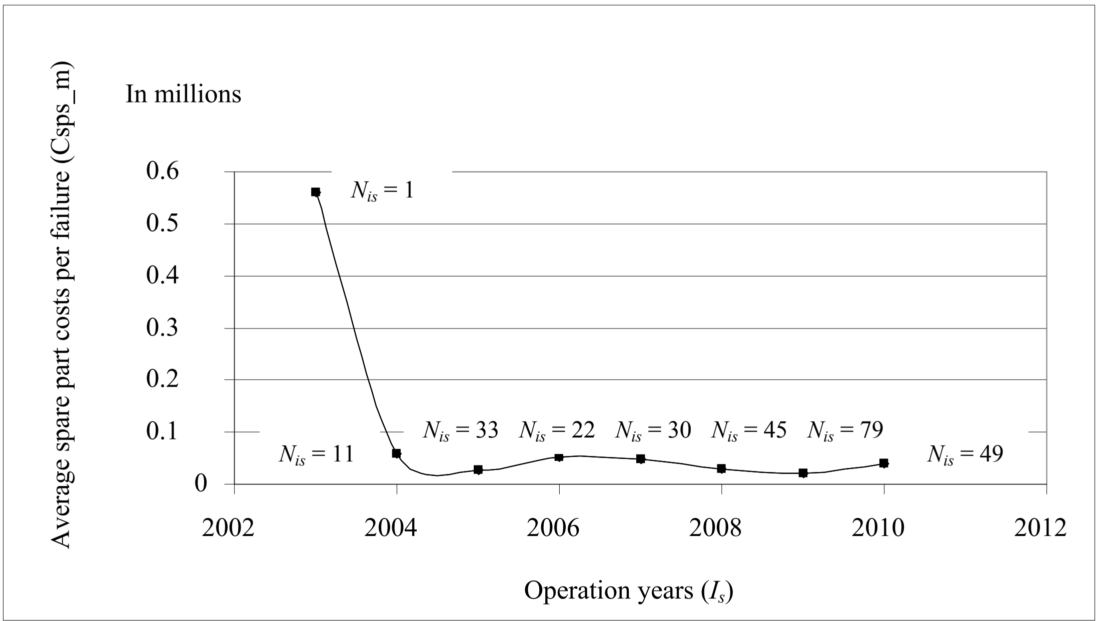

Figure 7.4 The average costs of providing spare part service per machine

The following section illustrates the reasons that the spare parts service data occurred in 2003 excluded from the engineering services cost model. The average spare parts service cost per failure and its fluctuated range are then estimated. The CER for estimating the total spare parts service costs for different numbers of machines is defined.

The average cost for providing spare parts service in 2003 was RMB 560,000, which was much higher than the cost for machines during the rest of their in-operation years. This phenomenon occurred due to a number of reasons.

First, as mentioned earlier, the 78 investigated machines belonged to the new production line, which was set up in 2003. Maintenance staff were less familiar and experienced with the XX machines, leading to a greater chance of requesting the wrong spare part or fixing it incorrectly. This might result in a higher cost of providing spare parts service. Second, the design and manufacturing method of the new machine may not be mature and could have hidden faults causing problems. This could also result in a higher cost of providing spare parts service. Third, as the new machine was launched in 2003, XX Company hardly had any historical data about breakdown parts related to the machine. Hence, the company tended to store more spare parts to ensure that the spare parts service was provided effectively and efficiently. Last but not least, because the customers hardly had any experience with the new design machine, the machine operator was more likely to control the machine inappropriately and hence break some components. Therefore, the XX Company probably offered more spare parts service to customers in 2003 than the coming years.

Based on these reasons, it was considered necessary to exclude the cost for providing spare parts service in 2003 from the engineering services cost model as the cost data occurred under different conditions.

To define the CER for providing spare parts service, the average spare parts cost per failure should be estimated. Figure 7.4 shows that the average spare parts cost per failure varied between RMB 21,108 and RMB 59,182 during 2004-2010.

Based on Table 7.9, the average spare parts cost per failure is estimated as approximately RMB 39,675. This is calculated as the sum of average spare parts cost per failure (Csps_m) occurring during 2004-2010 divided by 7 (Equation 7.5).

CER_2 is defined as the cost estimating relationship for predicting the total cost of providing spare parts service during seven in-operation years. The relationship between the total phone service cost (CER_2) and the number of years in operation (*j*) was determined from Equation 7.5 and Equation 7.2 respectively. The spare parts service costs (CER_2) are estimated by multiplying the average spare parts cost per failure (Csps_m) by the number of predicted failures that occurred in the j^{th} year. CER_2 is established as Equation 7.6:

CER_2 = average spare parts cost per failure x expected number of machine failures in the j^{th} year

$$= 39{,}675 \times N_{f_j}$$

$$= 39{,}675 \times 4.1382\, e^{-0.6269\, j} \times N_j \qquad \text{(Equation 7.6)}$$

3) Define the CER for providing on-site repair service.

When machine breakdowns occurred, the operator recorded the failure time and called the service provider to repair the machine. If the problem could not be resolved over the phone, the service provider sent maintenance staff to the customer's site to fix it. This type of engineering service is named the on-site repair service, which are often associated with repairing a broken part or replacing a spare part. In the majority of cases for the XX Company, the repairs focused on repairing the machine by replacing broken parts.

This on-site repair service is offered to the set of machines presented in Table 7.3 throughout the service contract life of each machine. Table 7.3 is redrawn here for clarity.

Table 7.3 The Number of Machines Sold and the Number of On-site Repairs Recorded

Year sold to customer (I_s)	***Number of machines sold that year (N_{s_i})***	***Number of On-site Repairs = Number of machine failures* in the *Is* year (N_{fi})**							
		2003 (Jan.-Dec.)	**2004 (Jan.-Dec.)**	**2005 (Jan. -Dec.)**	**2006 (Jan. -Dec.)**	**2007 (Jan. -Dec.)**	**2008 (Jan. -Dec.)**	**2009 (Jan. -Dec.)**	**2010 (Jan.-Dec.)**
2003	8	1	4	1	1	3	0	0	1
2004	15	-	7	20	4	3	1	2	0
2005	9	-	-	12	9	6	3	8	1
2006	9	-	-	-	8	12	13	24	4
2007	6	-	-	-	-	6	20	8	3
2008	11	-	-	-	-	-	8	22	4
2009	9	-	-	-	-	-	-	15	23
2010	11	-	-	-	-	-	-	-	13

Table 7.3 shows that eight machines were sold in 2003 and by the end of 2010 had been in operation for eight years, fifteen machines were sold in 2004 that had seven in-operation years as of 2010 and so on. The eight machines sold in 2003 had a single on-site repair service during their first year in-operation, and this increased to four in their second year of operation. The number of on-site repair service reduced to one in the third and fourth year, and so on. This on-site repair service is provided throughout the engineering service contract life of each machine. As noted previously, a single machine could breakdown numerous times or did not fail at all during the service period.

The XX Company assumed that the number of maintenance staff was hired based on the expected number of machine failures, whereas the number of on-site repair service was dependent on the actual number of machine failures. The XX Company also assumed that each member of maintenance staff was able to handle five on-site repair visits each year. These values are presented in Table 7.10.

As the costs of XX maintenance staff to provide on-site repair service was embedded in their salary, there were no separate costs for them to provide such service. However, based on the maintenance staff questionnaire (Chapter 6), it was discovered that around 80% of the maintenance staff time was spent on providing on-site service (the other 20% on phone service). Moreover, approximately 80% of the maintenance staff on-site working hours were spent on providing repair service, the remaining 20% being on visiting customer sites near to the repair service site. Hence, the cost of maintenance staff providing on-site repair service (Clj_v) is calculated as the product of total cost of maintenance staff (C_{lj}) multiplied by 80% times 80%. This is also presented in Table 7.10.

Table 7.10 Maintenance staff in the Is Year

Year sold to customer *(Is)*	Number of expected on-site repairs	Number of Maintenance Staff	Average cost per maintenance staff (Caverage_lj)	Total Maintenance Staff Salary (Clj=Number of Maintenance Staff × Caverage_lj)	Maintenance Staff Cost (Clj_v= Clj*80%*80%)
2003	20	4	22,636	90,545	57,949
2004	25	5	26,000	130,000	83,200
2005	35	7	20,400	142,800	91,392
2006	40	8	22,500	180,000	115,200
2007	45	9	25,556	230,000	147,200
2008	45	9	26,667	240,000	153,600
2009	50	10	27,000	270,000	172,800
2010	55	11	29,091	320,000	204,800

The costs incurred at the in-operation stage (years one to eight) of providing on-site repair service includes the costs for labour, travel, accommodation, meals, spare parts, subsidies for travel, bonus for providing good engineering services and overheads. The cost data collected from the industrial company is tabulated in Table 7.11. Based on Table 7.11, the total cost of on-site repair service (C_{6j}) is calculated as a sum of travel (C_{tpj}), accommodation (C_{aj}), meals (C_{mj}), subsidies (C_{sj}), bonus (C_{boj}) and labour costs (Clj_v) during eight in-operation years (Table 7.12).

Table 7.11 Total Cost Variables of On-site Repair Service (years 2003-2010)

Year sold to customer (I_s)	Total cost of travelling (C_{tpj})	Total cost of accommodation and meals ($C_{aj}+C_{mj}$)	Total cost of subsidies (C_{sj})	Total cost of bonus (C_{boj})	Total Maintenance Staff Salary (Clj)	Total cost of labour (Clj_v= Clj*80%*80%)
2003	100,000	20,000	21,000	60,000	90,545	57,949
2004	150,000	30,000	42,000	103,000	130,000	83,200
2005	215,500	80,000	70,000	156,000	142,800	91,392
2006	260,000	100,000	82,000	203,000	180,000	115,200
2007	380,000	152,000	110,000	261,000	230,000	147,200
2008	410,000	170,000	150,000	320,000	240,000	153,600
2009	430,000	200,000	180,000	360,000	270,000	172,800
2010	480,000	250,000	220,000	390,000	320,000	204,800

Table 7.12 Total Cost of On-site Repair Service (years 2003-2010)

Year sold to customer (I_s)	Total cost of on-site repair service ($C_{6j} = C_{tpj}+C_{aj}+C_{mj}+C_{sj}+C_{boj}+C_{lj\_v}$)
2003	258,949
2004	408,200
2005	612,892
2006	760,200
2007	1,050,200
2008	1,203,600
2009	1,342,800
2010	1,544,800

Based on Tables 7.3 and 7.12, the average on-site repair service costs per failure are calculated and presented in Table 7.13. The average on-site repair service cost per failure ($C_{average\_6j}$) is calculated as the quotient of total costs of providing on-site service divided by the total number of failures in the corresponding year.

Table 7.13 shows that one on-site repair was provided in 2003, eleven on-site repairs were performed in 2004 and so on. Moreover, the total costs for providing this one on-site repair service in 2003 was RMB 258,949, hence the average on-site repair cost per failure was RMB 258,949. The total costs for providing eleven on-site repair services in 2004 was RMB 408,200, therefore the average on-site repair cost per failure was RMB 37,109 and so on.

Table 7.13 The Average on-site repair cost per failure in their *Is* Years

Year sold to customer *(I_s)*	**Total number of machine failures in the I_s year *(N_{is})***	**Average on-site repair cost per failure ($C_{average\_6j} = C_{6_j} / N_{is}$)**
2003	1	258,949
2004	11	37,109
2005	33	18,572
2006	22	34,555
2007	30	35,007
2008	45	26,747
2009	79	16,997
2010	49	31,527

The average on-site repair costs per failure and the corresponding in-operation years are shown in Figure 7.5. It showed that the average on-site repair cost per failure fluctuated during 2003-2010.

When the number of on-site repair service increased significantly from 1 to 11 in 2003 and 2004 respectively, the average cost of providing a single on-site repair service dropped by nearly 86%. The first year of providing such a service (2003) was more costly than that for the rest of the operation years (2004-2010).

When the number of machine failures increased significantly from 11 to 33 in 2004 and 2005 respectively, the average on-site repair cost per failure reduced by around 50%. In contrast, the number of machine failures increased from 30 to 38 in 2006 and 2007 respectively, this service cost increased by around 1% from RMB 34555 to RMB 35007 correspondingly. Furthermore, when the number of machine failures increased from 45 to 49 in 2008 and 2010, the average on-site repair cost per failure in 2010 was increased by nearly 18% over the year 2008. Hence, as discussed previously in 2003 the maintenance staff were less familiar and experienced with the XX machines in the machine's first operation year, it may take them longer to fix the problem. The cost of accommodation/meals and subsidies for travelling might be more expensive. Thus, the year 2003 was taken as an outlier and the 2003 data was excluded when calculating the CER for providing on-site repair service.

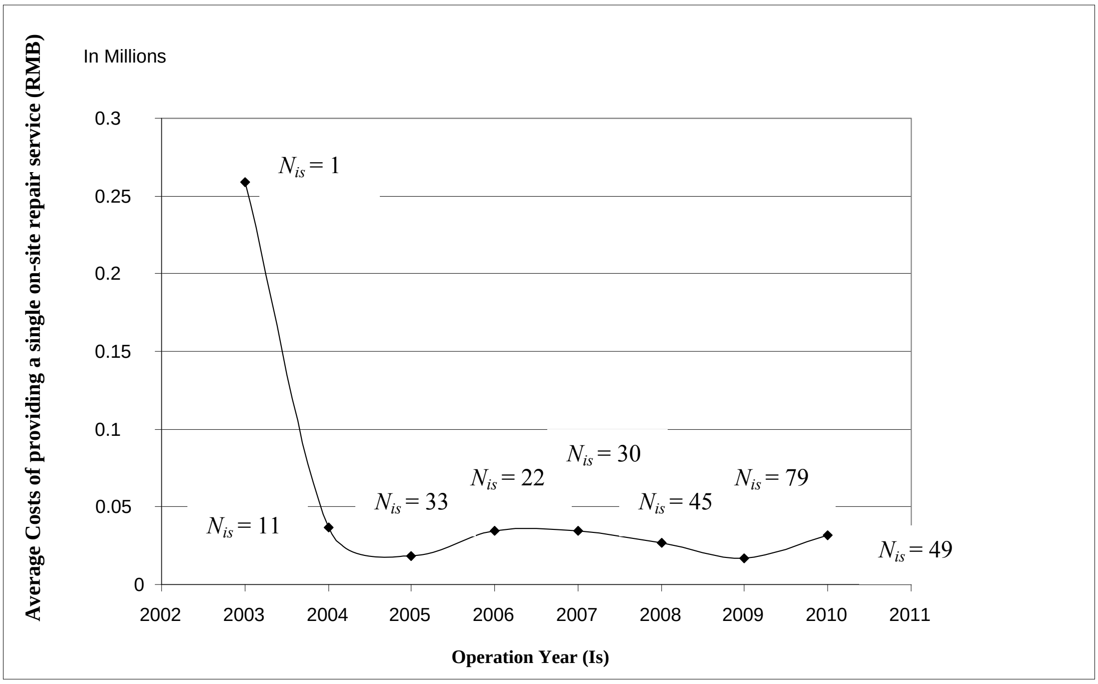

Figure 7.5 Average on-site repair service costs per failure

To define the CER for providing on-site repair service, the average on-site repair cost per failure should be estimated. Figure 7.4 shows that the average on-site repair cost per failure varied RMB 16997 and RMB 37109 during 2004-2010.

Based on Table 7.14, the average on-site repair service cost per failure is estimated as approximately RMB 28,645. This is calculated as the sum of average on-site repair service cost per failure ($C_{average\_6j}$) occurring during 2004-2010 divided by 7 (Equation 7.7).

CER_3 is defined as the cost estimating relationship for predicting the total cost of providing on-site repair service during seven in-operation years. The relationship between the total phone service cost (CER_3) and the number of years in operation (j) was determined from Equation 7.7 and Equation 7.2 respectively. The on-site repair service costs (CER_3) are estimated by multiplying the average on-site repair service cost per failure ($C_{average\_6j}$) by the expected number of failures that occurred in the j^{th} year. CER_3 is established as Equation 7.8:

CER_3 = average on-site repair cost per failure × expected no. of machine failures in the j^{th} year

$$= 28{,}645 \times N_{f_j}$$

$$= 28{,}645 \times 4.1382\, e^{-0.6269\, j} \times N_j \qquad \text{(Equation 7.8)}$$

4) Define the CER for providing engineering services to the XX customers.

As the XX engineering services includes the service of phone, spare parts and on-site repair visits, the total cost for providing such services in the jth year is estimated as the sum of CER_1, CER_2 and CER_3. Moreover, the total overhead cost is a proportion of the total cost for providing such services. Based on Equations 7.4, 7.6 and 7.8, the expected total engineering services cost in the j^{th} year, C_{es}, is

C_{es} = (CER_1 + CER_2 + CER_3) × (1+overheads%)

$$= (2002 \times 4.1382e^{-0.6269j} \times N_j + 39{,}675 \times 4.1382e^{-0.6269j} \times N_j + 28{,}645 \times 4.1382e^{-0.6269j} \times N_j)$$
$$\times (1 + \text{overheads\%}) \qquad \text{(Equation 7.9)}$$

7.2.4 Engineering Services Cost Model

The engineering services cost model is created through ustilising the parametrics (the two performance factors and CERs 1-4) and the bathtub failure model. It is mainly based on the 2 performance factors and 4 CERs. These performance factors and CERs are summarised as:

Expected machine failure rate in the j^{th} year, $\lambda_j = 4.1382e^{-0.6269j}$ (Equation 7.1)

Expected number of machine failures in the j^{th} year, $N_{f_j} = \lambda_j \times N_j = 4.1382\, e^{-0.6269\, j} \times N_j$

(Equation 7.2)

CER_1 = average phone cost per failure x expected number of machine failures in the j^{th} year

$$= 2002 \text{ x } N_{f_j}$$

$$= 2002 \text{ x } 4.1382e^{-0.6269j} \text{ x } N_j \qquad \text{(Equation 7.4)}$$

CER_2 = average spare parts cost per failure x expected number of machine failures in the j^{th} year

$$= 39{,}675 \text{ x } N_{f_j}$$

$$= 39{,}675 \text{ x } 4.1382e^{-0.6269j} \text{ x } N_j \qquad \text{(Equation 7.6)}$$

CER_3 = average on-site repair cost per failure x expected number of machine failures in the jth year

$= 28{,}645 \times N_{f_j}$

$= 28{,}645 \times 4.1382e^{-0.6269j} \times N_j$ (Equation 7.8)

$C_{es} = (CER_1 + CER_2 + CER_3) \times (1+\text{overheads}\%)$

$= (2002 \times 4.1382e^{-0.6269j} \times N_j + 39{,}675 \times 4.1382e^{-0.6269j} \times N_j + 28{,}645 \times 4.1382e^{-0.6269j} \times N_j)$
$\times (1+\text{overheads}\%)$

(Equation 7.9)

The expected number of failures, N_{f_j}, (Equation 7.2) is dependent on the expected machine failure rate, $\lambda_{j,}$ (Equation 7.1), whereas CERs 1-3, are dependent on the expected machine failure rate (λ_j). Hence, if the expected machine failure rate ($\lambda_{j,}$) is validated, then the CER_1, $_2$ and $_3$ is validated, then CERs 1-3 are validated and the total engineering services cost (C_{es}) is also validated. In the next chapter, how to validate the engineering services cost model by validating the expected machine failure rate is presented.

7.3 Summary

The focus of this chapter was to demonstrate how the engineering services cost model was created for use in estimating the cost of the XX Company providing engineering services. The outcome being that the performance factors and the cost estimating relationships, i.e. the core parametrics for the cost model was identified. To achieve this, in-operation cost related data (years 2003-2010) was collected from the XX Company. The relationship between machine failure rate and the number of in-operation years was identified. Utilising the data from the XX Company of the machine failure records from 2003-2010, it was found that the correlation and correlation coefficient between the number of years in-operation and the machine failure rate are $\lambda_j = 4.1382e^{-0.6269j}$ and 0.9653. This suggested that as the in-operation years of machines increase, the reliability of the machine would improve for the first eight in-operation years. This was the first performance factor identified from the data. Based on this finding, the performance factor for predicting the number of failures in the jth year was identified.

Four Cost Estimating Relationships were also identified for use in the cost model to predict the future costs of providing phone service, spare parts service and on-site repair service. Based on the performance factors and CERs 1-3, the CER for predicting the total engineering services cost for servicing different numbers of machines in different operation years (C_{es}) was established.

The relationships were all utilised to create a cost-estimating model in Microsoft Excel. In the next chapter, how engineering services cost model was validated is presented.

Chapter 8 Validation and Extension of the Engineering Services Cost Model

This chapter focuses on the validation and extension of the engineering services cost model. The validation and extension process is separated into four steps. First, the concept of the cost model was examined and validated by two groups of experienced experts from the XX Company. In particular, the model's process/logic, specifications, assumptions, performance factors and CERs were carefully scrutinised. Second, splitting the machine data into mechanical and electrical data to ascertain whether the findings were consistent and could be replicated. Third, the first eight years of machine failure rate predicted by the service experts were used to validate the engineering services cost model. Finally, the machine failure rate predicted by the service experts covering a 15 year period was used to extend the model for estimating the engineering services cost. The 15 year period was selected to ascertain whether the bathtub failure model was appropriate for use. The validation and extension processes are described in this chapter.

8.1 Introduction

To ensure the engineering services cost model was valid, validation of the model was conducted. Validation is usually the process of checking and examining the model is sufficiently accurate for the intended application of the model (Sargent, 2005). It is usually regarded as building the right model, which represents the real system (Kleijnen, 1995).

The validation and extension process is separated into four steps in this chapter.

1) The concept of the engineering services cost model was examined and validated by two groups of experienced experts from the XX Company (Section 8.2). By applying the face validity technique, the model's process/logic, specifications, assumptions and the CERs were carefully scrutinised to ensure they were correct. Meanwhile, the cost model was also checked to ensure it represents the real system.

2) The cost model was validated by historical data. In this step the machine failure data used to create the model was split into mechanical and electrical failure data.

The model is validated if the failure curve for the machine matched with the individual failure curves for the mechanical and electrical failure data. This type of validation could be named as the historical data validation, a common technique used for validating the model (Sargent, 2005).

3) The cost model was validated by expert opinions. The estimated values generated from the model and the values (1-8 years of machine failures) predicted by the XX experts were compared in order to enhance the credibility and validity of the overall cost model. This type of validation is called the operational validation and is used to ensure the model's output behaviour has sufficient accuracy to meet the purpose of the model and reflect the real system (Sargent, 2005).

4) The cost model was extended by expert opinions. The machine failure rate predicted by the service experts covering a 15 year period was used to extend the model for estimating the engineering services cost.

The next sections discuss how the four steps of validation and extension were undertaken.

8.2 Step 1: Validation for the Concept of the Cost Model

During the industrial visit, two sets of structured meetings were conducted with two groups of experienced XX staff in order to validate the concept of the engineering services cost model. The first one was carried out with a group of six maintenance staff, whereas the second one was conducted with two financial staff. The background and methods of this structured meeting was introduced. A general discussion and analysis about the expected outcomes from the meeting were also presented.

Table 8.1 summarises the general background of the two sets of structured meetings. This includes meeting information related to the date, duration, place, conductor, target, and purpose.

Meeting Method:

Two separate sets of face-to-face meetings were conducted with two groups of internal staff from the XX Company. The meeting dates were selected based on the availability of the staff, whereas, the meeting targets were separated into two groups based on the speciality and experience of the staff. The first group consisted of six experienced maintenance staff that had worked in the XX After-sale Service Department between five and fifteen years. The second group consisted of two knowledgeable financial staff that had worked in the XX Finance Department for approximately ten years. Before the meeting, each participant was informed of the time, duration and purpose of the meeting.

Table 8.1 The background information related to the two sets of structured meetings

Date and Duration	1) 19/09/2011, approximately one and half hour with six maintenance staff 2) 26/09/2011, approximately one and half hour with two financial staff
Place	XX Company
Conductor	The researcher of this thesis
Target	1) Maintenance staff from the After-sales Service Department 2) Financial staff from the Financial Department
Purpose	The following points were examined without presenting the engineering service cost model: 1) To check whether the process of estimating the future costs of providing engineering services to XX customers matched with experts' experience. 2) To check whether the logic of building the engineering services cost model met with experts' understanding. 3) To check whether the specification of the conceptual cost model reflected the real system. 4) To check whether the assumptions of building the model matched with experts' experience. 5) To check whether the cost-related variables, key relationships and CERs met with experts' understanding. 6) To check whether the estimated values from the model matched with experts' experience. 7) To ascertain ways to improve or test the engineering services cost model.

Although the two sets of meetings were conducted with different people at different times, the purpose and assumptions were identical (Table 8.1). More importantly, the process and the method for conducting these two meetings were also structured and consistent.

In addition, each of the meetings was conducted with the same questionnaire (Appendix C). This questionnaire was prepared in a word document. It was then printed in hard copy and handed to each member of staff at the meeting. During the meeting, respondents completed the questionnaire and the researcher took notes of the meetings. Notes were organised and presented in the *Meeting Outcome* Section.

Meeting Outcome:

The following points were agreed with the eight experienced staff (including six maintenance staff and two financial staff).

- The process of estimating the future cost of providing engineering services to XX customers seemed reasonable.
- The logic of building the engineering service cost model was sensible.
- The scope of the cost model was considered acceptable within the limited research period.
- The specifications of the cost model were realistic reflecting the real system.
- The assumptions for developing the model were realistic and reasonable.
- The performance factors and the CERs were sounded reasonable.

The following points were agreed with the six experienced maintenance staff.

- The performance factors were considered acceptable as the pattern of overall machine failure rate against service years matched with the real system based on maintenance staff's experience. This was also approved by one of the respondents who is the head of the After-sales Service Department.

The following points were agreed with the two experienced financial staff.

- The CERs for predicting the future costs of providing phone service, spare parts service and on-site repair service were considered acceptable by the two experience financial staff, including one who is the head of the Finance Department.

Overall, six out of eight staff selected 90% satisfaction on the engineering service cost model, whereas one circled an 80% satisfaction level and the other chose 70%.

Two Key Recommendations for Further Improvements:

1) The pattern of on-site repair service could be checked and validated by examining the pattern of mechanical failures and electrical failures. From maintenance staff point of view, if the model was valid, the pattern of on-site repair service should match with the individual trends generated from the mechanical failures and electrical failures respectively. This was because the pattern of on-site repair service represents the failure pattern of the overall machine. Each machine failure could consist of more than one mechanical or electrical failure. Although the data were not identical for different cases, the machine failure pattern for each case should be similar.

2) The financial staff suggested that the total overhead cost could be assumed as approximately 5% of the total engineering service cost each year.

Based on the recommendations from eight experts, the engineering service cost model was validated. The following sections described how to validate the cost model by splitting the machine failure data into mechanical and electrical failure data.

8.3 Step 2: Validation for the Cost Model – Historical Data

Based on the experts' suggestions from the meeting described in Section 8.2, the engineering services cost model was validated by historical data. This indicated that examining the patterns of mechanical failures and electrical failures respectively validated the trend of machine failure rate.

Based on expert opinions, the total number of machine failures includes the number of mechanical failures and electrical failures. As a single machine could have more than one mechanical/electrical failure or did not fail at all during service years 2003-2010, the total number of machine failures did not necessary equal to the sum of total number of mechanical failures and electrical failures. However, the general trend of the overall machine failures (Chapter 7: Equation 7.1) should match with the individual trends of mechanical failures and electrical failures in order to validate the engineering services cost model.

The following section describes how the data related to mechanical failures and electrical failures occurred during 2003-2010 was collected and analysed. This set of data was then used to determine whether the engineering services cost model was validated and reflected the real system.

8.3.1 Mechanical Failure Trend

a) Collect and analyse the data related to mechanical failures occurring during 2003-2010

In Chapter 7, the trend and the performance factor for predicting the overall machine failure rate were established (Chapter 7: Equation 7.1). In this section, by adapting the same process, the pattern for predicting the mechanical failure on the same group of machines were identified and analysed.

In total there were 78 machines from the same production line sold during 2003-2010. The number of machines sold and the number of mechanical failures occurring during the 2003-2010 period are summarized in Table 8.2.

Table 8.2 The Number of Machines Sold and the Number of Mechanical Failures Recorded

Year sold to customers (I_s)	Years in operation (i)	Number of machines sold that year (Ns_i)	Number of Mechanical Failures (M_{ij})							
			1st year in operation (j = 1)	2nd year in operation (j = 2)	3rd year in operation (j = 3)	4th year in operation (j = 4)	5th year in operation (j = 5)	6th year in s operation (j = 6)	7th year in operation (j = 7)	8th year in operation (j = 8)
2003	1	8	1	0	1	1	1	0	1	0
2004	2	15	6	14	2	2	1	1	0	-
2005	3	9	9	4	2	6	1	1	-	-
2006	4	9	15	6	26	8	2	0	-	-
2007	5	6	21	3	4	4	0	-	-	-
2008	6	11	19	8	4	3	-	-	-	-
2009	7	9	35	19	0	-	-	-	-	-
2010	8	11	36	10	-	-	-	-	-	-

Table 8.2 shows that the eight machines sold in 2003 had a total of one mechanical failure during their first year in-operation, and this reduced to zero in their second

year of operation. The mechanical failure increased to one in the third, fourth and fifth years, and so on.

Based on Table 8.2, the total number of machines and total number of mechanical failures are presented in Table 8.3. The same sets of machines for identifying the overall machine failure trend were used to examine the mechanical failure rate. Therefore, there are 78 machines in-operation for at least one year, 67 out of 78 were in operation for at least two years, and so on. More importantly, the 78 machines had 142 mechanical failures in their first operation year, 67 machines had 64 mechanical failures in the second operation year, and so on.

Table 8.3 Number of Machines in Operation for at Least i Years; Number of Mechanical Failures and Mechanical Failure Rate in the jth Year of Operation

Years in service (*i*)	Number of machines in operation for at least i years (N_i)	Year of operation (*j*)	Number of mechanical failures in the j^{th} year of operation (M_{f_j})	Mechanical failure rate in the j^{th} year of operation ($\lambda_{mj} = 100\, M_{f_j} / N_i$)
1	$\sum_{i=1}^{8} N_{s_i} = 78$	1	$\sum_{i=1}^{8} M_{f1} = 142$	182%
2	$\sum_{i=1}^{7} N_{s_i} = 67$	2	$\sum_{i=1}^{7} M_{f2} = 64$	96%
3	$\sum_{i=1}^{6} N_{s_i} = 58$	3	$\sum_{i=1}^{6} M_{f3} = 39$	67%
4	$\sum_{i=1}^{5} N_{s_i} = 47$	4	$\sum_{i=1}^{5} M_{f4} = 24$	51%
5	$\sum_{i=1}^{4} N_{s_i} = 41$	5	$\sum_{i=1}^{4} M_{f5} = 5$	12%
6	$\sum_{i=1}^{3} N_{s_i} = 32$	6	$\sum_{i=1}^{3} M_{f6} = 2$	6%
7	$\sum_{i=1}^{2} N_{s_i} = 23$	7	$\sum_{i=1}^{2} M_{f7} = 1$	4%
8	$\sum_{i=1}^{1} N_{s_i} = 8$	8	$\sum_{i=1}^{1} M_{f8} = 0$	0%

b) Establish the mechanical failure trend and the costing relationship

The relationship calculated between the machine mechanical failure rate and the number of years in operation is shown in the last column of Table 8.3. The actual mechanical failure rates are shown in Figure 8.1 as the dashed line. In the first year of operation for the 78 machines a mechanical failure rate of 182% occurred. This means that on average, every machine had two failures during its first year in operation. However, in year two this reduced significantly to approximately 95% based on a sample of 67 machines. During the third and fourth in-operation years, the machines failed less frequently. After machines had been in operation for more than four years, the failure rates reduced significantly to less than 15%.

By following the same approach for predicting the overall machine failure rate (Chapter 7: Equation 7.1), an exponential trend curve for predicting the mechanical failure rate was plotted in Figure 8.1. It was also found that the correlation and correlation coefficient between the number of year's in-operation and the expected mechanical failure rate are $\lambda_{mj}= 3.7108e^{-0.6245j}$ and 0.9667, where λ_{mj} represented expected mechanical failure rate and j indicated the number of year's in-operation. This relationship is defined as Equation 8.1.

$$\lambda_{mj}= 3.7108e^{-0.6245j} \qquad \text{(Equation 8.1)}$$

In general, as the correlation coefficient becomes closer to 1, the established relationship is more valid and reliable (Huang et al., 2011). Hence, the correlation coefficient of 0.9667 shows that there were a strong correlation between the expected mechanical failure rate and the number of years in operation for the XX machines.

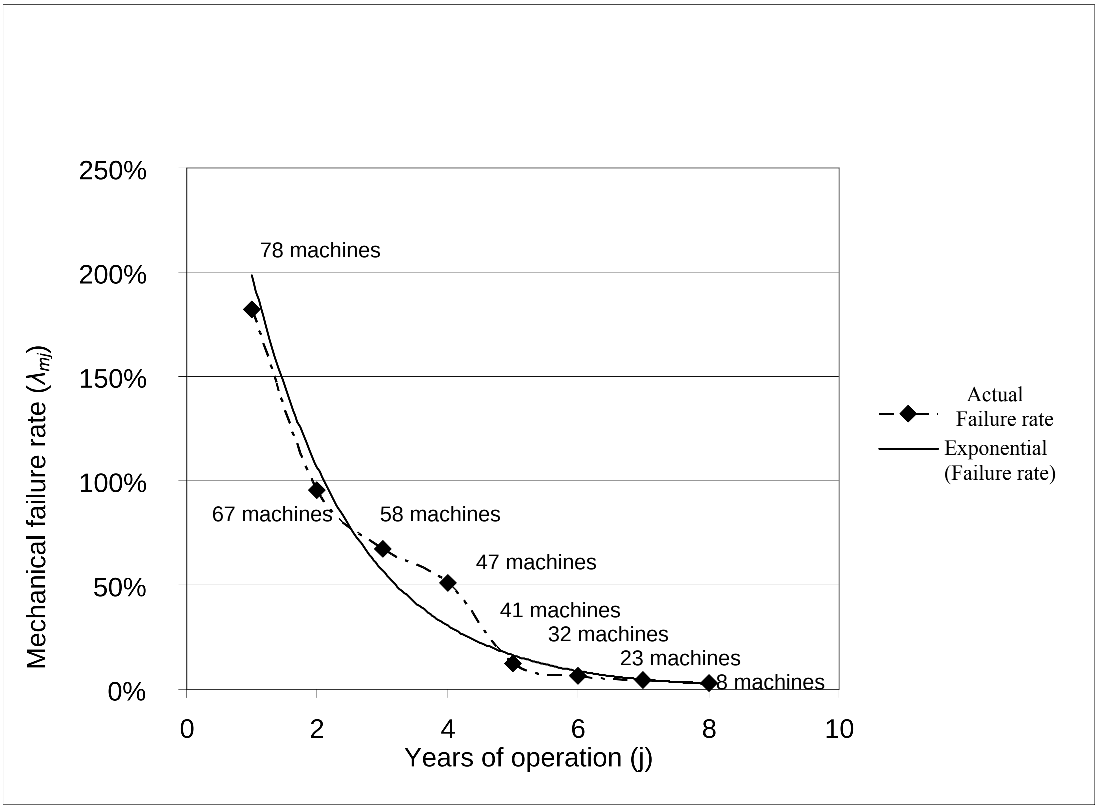

Figure 8.1 The relationship between mechanical failure rate and years in operation

c) Compare the expected mechanical failure trend (Chapter 8: Equation 8.1) with the expected machine failure trend (Chapter 7: Equation 7.1)

Figure 7.2 The relationship between machine failure rate and years in-operation (1-8yrs)

In Chapter 7, the overall trend for predicting the machine failure rate was estimated by an exponential distribution (Figure 7.2 is duplicated here for comparison). During the first year in-operation, the expected machine failures were significantly higher than that at the rest of the years. They then reduced greatly to ~100% in the second year of operation based on a sample of 67 machines. During the third and fourth in-operation years, the machine failed less frequently. After the machines had been in-operation for more than four years, the expected failure rate reduced significantly to less than 13%. From Chapter seven, the relationship between the number of years in-operation and the overall expected machine failure rate was established as $\lambda_j = 4.1382e^{-0.6269j}$ (Chapter 7: Equation 7.1) with the correlation coefficient being 0.9653, where λ_j represented the overall machine failure rate and j indicated the number of years in-operation.

Comparing Figure 7.2 with Figure 8.1, the difference between the parameters -0.6269 and -0.6245 of the exponential distribution for both figures is small, which indicates that the expected mechanical failure trend is similar to the expected machine failure trend. Therefore, in terms of mechanical failures, using the exponential distribution to establish the relationship (Chapter 7: Equation 7.1) for predicting the overall machine failure rate is an appropriate method.

Moreover, in Figures 7.2 and 8.1, both correlation coefficients are close to 1, which means that both the expected mechanical failure rate $\lambda_{mj} = 3.7108e^{-0.6245j}$ and the expected machine failure rate $\lambda_j = 4.1382e^{-0.6269j}$ (Chapter 7: Equation 7.1) are validated.

8.3.2 Electrical Failure Trend

a) Collect and analyse the data related to electrical failures occurred during 2003-2010

In Chapter 7, the trend and the performance factor for predicting the overall machine failure rate were established. In this section, by adapting the same process, the trend for predicting the electrical failure on the same groups of machines were identified and analysed.

In total there were 78 machines from the same production line sold during 2003-2010. The number of machines sold and the number of electrical failures occurring during the 2003-2010 period are summarised in Table 8.4.

Table 8.4 The Number of Machines Sold and the Number of Electrical Failures Recorded

Year sold to customers (I_s)	Years in operation (i)	Number of machines sold that year (Ns_i)	Number of Electrical Failures (E_{fj})							
			1st year in operation (j = 1)	2nd year in operation (j = 2)	3rd year in operation (j = 3)	4th year in operation (j = 4)	5th year in operation (j = 5)	6th year in operation (j = 6)	7th year in operation (j = 7)	8th year in operation (j = 8)
2003	1	8	3	1	1	2	0	0	0	0
2004	2	15	6	6	0	0	0	1	0	-
2005	3	9	5	8	2	2	1	0	-	-
2006	4	9	4	5	20	10	2	1	-	-
2007	5	6	14	4	3	0	1	-	-	-
2008	6	11	8	5	1	3	-	-	-	-
2009	7	9	16	4	0	-	-	-	-	-
2010	8	11	18	7	-	-	-	-	-	-

Table 8.4 shows the eight machines sold in 2003 had a total of three electrical failures during their first year in-operation, and this reduced to one during their second and third year of operation. The electrical failure increased to two in the fourth year, and so on.

Based on Table 8.4, the total number of machines and total number of electrical failures are presented in Table 8.5. Electrical failure rate was identified based on the same sets of machines for identifying the overall machine failure rate. Hence, it shows that there are 78 machines in-operation for at least one year, 67 out of 78 were in operation for at least two years, and so on. Furthermore, the 78 machines had 74 electrical failures in their first operation year, 67 machines had 40 electrical failures in the second operation year, and so on.

Table 8.5 Number of Machines in Operation for at Least i Years; Number of Electrical Failures and Electrical Failure Rate in the jth Year of Operation

Years in service (i)	Number of machines in operation for at least i years (N_i)	Year of operation (j)	Number of electrical failures in the j^{th} year of operation (E_{f_j})	Electrical failure rate in the j^{th} year of operation ($\lambda_{ej} = 100\, E_{f_j} / N_i$)
1	$\sum_{i=1}^{8} N_{s_i} = 78$	1	$\sum_{i=1}^{8} E_{f1} = 74$	95%
2	$\sum_{i=1}^{7} N_{s_i} = 67$	2	$\sum_{i=1}^{7} E_{f2} = 40$	60%
3	$\sum_{i=1}^{6} N_{s_i} = 58$	3	$\sum_{i=1}^{6} E_{f3} = 27$	47%
4	$\sum_{i=1}^{5} N_{s_i} = 47$	4	$\sum_{i=1}^{5} E_{f4} = 17$	36%
5	$\sum_{i=1}^{4} N_{s_i} = 41$	5	$\sum_{i=1}^{4} E_{f5} = 4$	10%
6	$\sum_{i=1}^{3} N_{s_i} = 32$	6	$\sum_{i=1}^{3} E_{f6} = 2$	6%
7	$\sum_{i=1}^{2} N_{s_i} = 23$	7	$\sum_{i=1}^{2} E_{f7} = 0$	0%
8	$\sum_{i=1}^{1} N_{s_i} = 8$	8	$\sum_{i=1}^{1} E_{f8} = 0$	0%

b) Establish the electrical failure trend and the costing relationship

The relationship calculated between the electrical failure rate and the number of years in operation is shown in the last column of Table 8.5 and presented in Figure 8.2 as the dashed line. From Figure 8.2, a 95% electrical failure rate occurred on 78 machines during their first year in-operation, which means that on average, every machine had around one electrical failure during its first year in operation. However, in year two this reduced significantly to approximately 60% based on the same sample of 67 machines. During the third and fourth in-operation years, the electrical part of the machines failed less frequently. After machines had been in operation for more than four years, the electrical failure rates reduced significantly to less than 10%.

By following the same approach for predicting the overall machine failure rate (Chapter 7: Equation 7.1), an exponential trend curve for predicting the electrical failure rate was plotted in Figure 8.3. It was also found that the correlation and correlation coefficient between the number of years in-operation and the machine electrical failure rate are λ_{ej}= 1.9619e$^{-0.5463j}$ and 0.967, where λ_{ej} represented machine electrical failure rate and j indicated the number of years in-operation. This relationship is defined as Equation 8.2.

$$\lambda_{ej} = 1.9619e^{-0.5463j} \qquad \text{(Equation 8.2)}$$

In general, as the correlation coefficient becomes closer to 1, the established relationship is more valid and reliable (Huang et al., 2011). Hence, the correlation coefficient of 0.967 shows that there were a strong correlation between the expected electrical failure rate and the number of years in operation for the XX machines.

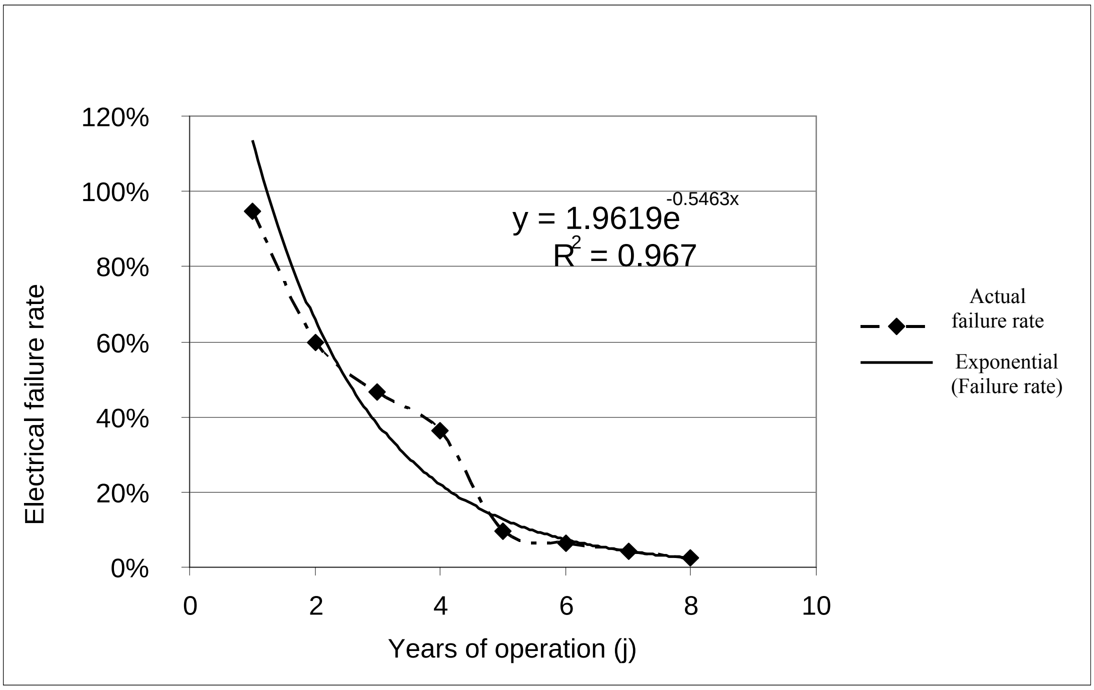

Figure 8.2 The relationship between electrical failure rate and years in operation

c) Compare the expected electrical failure trend (Chapter 8: Equation 8.2) with the expected machine failure trend (Chapter 7: Equation 7.1)

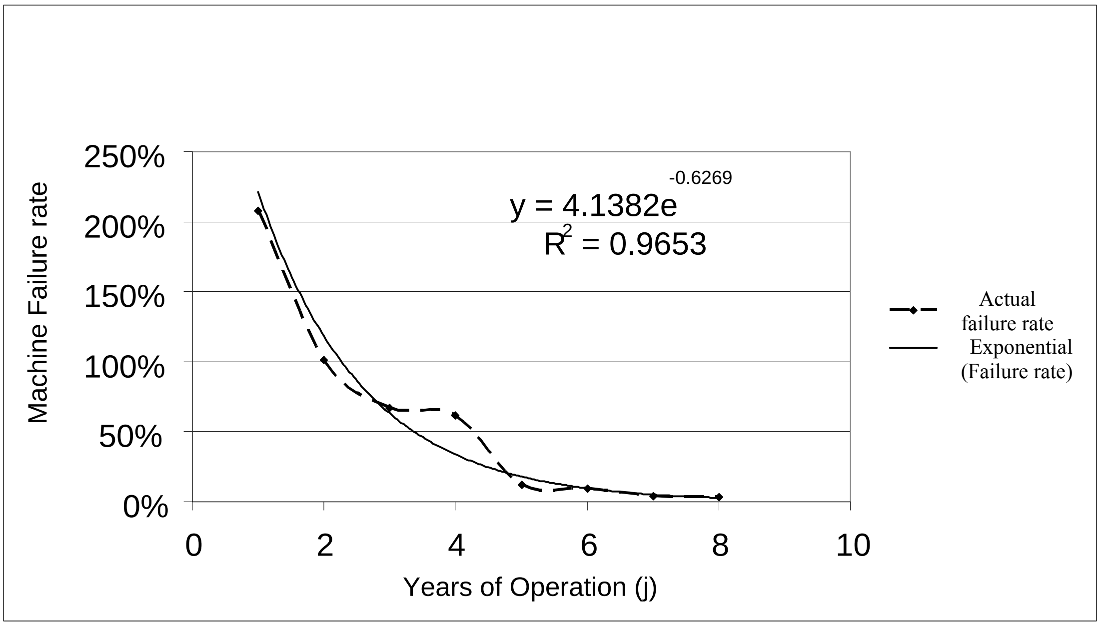

Figure 7.2 The relationship between machine failure rate and years in-operation (1-8yrs)

In Chapter Seven, the overall trend for predicting the machine failure rate was estimated by an exponential distribution (Figure 7.2 is duplicated here for clarity). The relationship between the number of years in-operation and the overall expected machine failure rate is established as λ_j= 4.1382e$^{-0.6269j}$ (Chapter 7: Equation 7.1) with the correlation coefficient of 0.9653, where λ_j represented the overall machine failure rate and *j* indicated the number of years in-operation.

Comparing Figure 7.2 with Figure 8.2, the difference between the parameters -0.6269 and -0.5463 of the exponential distribution for both figures is small, which indicates that the expected electrical failure trend is similar to the expected machine failure trend. Therefore, in terms of electrical failures, using exponential distribution to establish the relationship (Chapter 7: Equation 7.1) for predicting the overall machine failure rate is an appropriate method.

Moreover, in Figures 7.2 and 8.2, both correlation coefficients are close to 1, which means that both the expected electrical failure rate λ_{ej}= 1.9619e$^{-0.5463j}$ and the expected machine failure rate λ_j= 4.1382e$^{-0.6269j}$ (Chapter 7: Equation 7.1) are validated.

Since both the mechanical failure trend and the electrical failure trend matched with the overall machine failure trend, Equation 7.1 is validated. As mentioned in Chapter 7, Equation 7.2 is dependent on Equation 7.1. Since Equation 7.1 is checked and verified, Equation 7.2 can be applied to estimate the costs of providing phone services, spare part service and on-site repair service. Hence, the engineering services cost model is validated by checked with historical data of mechanical and electrical failures.

8.4 Step 3: Validation for the Cost Model – Experts Opinions (1-8 years)

To validate the engineering services cost model, the first eights years of machine failure rate predicted by the experts were utilised through using two scenarios. The aim here was to determine whether the cost model results were representative of the expert's view of the machine failure rates. Moreover, 15 years of machine failure rate predicted by the service experts were utilised to extend the cost model, which will be described in Section 8.5.

This section describes the reasons for conducting these two scenarios. It also presents how two different scenarios were tested. First, based on Validation and Extension Scenario, the opinions of the experts' were gathered through a Structured Meeting. Second, based on Validation Scenario, cost estimating results developed by the engineering services cost model were presented. Third, Expert opinions (Validation and Extension Scenario) and the engineering service cost model (Validation Scenario) were compared and analysed. For this purpose Validation and Extension Scenario was as follows.

8.4.1 Validation and Extension Scenario – expert opinions

Validation and Extension Scenario:

We wish to sell 100 XX machines from the same production line. Each machine was sold to a different customer in Mainland China. These customers are requesting that we enter into engineering service contract with them. The options are different *contract lengths--one, three, five, seven, nine, eleven, thirteen and fifteen years. What are the machine failure rates for 100 machines per year at different contract lengths?*

The need for Validation and Extension Scenario – provision of CERs when there is no historical data and in this case to ascertain whether the bathtub failure model is appropriate when determining the engineering services costs.

It was discovered that the XX Company had provided engineering services to two generations of XX machines. The first generation of the XX machines was sold before 2003, whereas the second generation of the same type of machines were sold from 2003 onwards. The failure rate data and some of the associated costs were available from 2003-2010. Hence, the engineering services cost model was developed based on eight years of in-operation data from the second generation of the machines. Consequently, the resulting engineering services cost model was able to predict the expected machine failure rate for the first eight in-operation years, and from this the CERs and the associated costs for the engineering services provision were generated. The results from the eight in-operation years depicted that the number of machine failures tended to reduce over the years, and the failure rates followed the early stage of a bathtub failure model. This is a common failure pattern for repairable components of a product (O'Connor, 1991; Dhillon, 2010). It was suspected that the machine failure rate might increase again after a certain number of in-operation years, which should match the later stage of the bathtub failure model. However, the lifespan of the XX machine was unknown and the point where the failure rates would be expected to raise was also not known.

To face this challenge, it was necessary to predict when the bathtub failure model would be expected to increase, as there were no physical data records that could be used. From initial meetings and discussions with the case study company it was noted that four experienced maintenance staff had worked in the company for ten to fifteen years. Although the design and appearance of the XX machine had been improved and upgraded over the past fifteen years, the general failure pattern for the same type of machines were assumed to be similar. This was deemed a sound assumption, as the changes had been incremental and no actual significant changes in the machine design and set-up had occurred, i.e. the machines were similar. This meant that the first generation of the XX machines sold earlier than 2003 may have a similar failure pattern against the second generation of the same type of machines sold after 2003. Therefore, the four maintenance staff should be able to predict the lifespan of the XX machine based on their experience and knowledge in the field. The first step of Validation and Extension Scenario was to elicit the staff knowledge for use in the engineering services cost model to predict when the bathtub would commence its upward turn. The second step was then to present the cost estimation models findings to the experts and use their feedback within the validation process. The final stage was then to compare the expert opinions with the CERs and costs generated from the actual data available in the company.

Structured Meeting – Gathering the expert opinions

Due to reasons discussed in the previous section, a structured meeting was held with the four experienced maintenance staff during the fourth visit to the XX Company. During the meeting, the machine failure rate was estimated by the maintenance staff based on the Validation and Extension Scenario.

Within this section, the background and methods of structured meeting is introduced. A general discussion and analysis about the outcomes of the meeting are also presented. The information in Table 8.6 shows the general background of the meeting. It includes meeting information related to the date, duration, place, conductor, target, and purpose.

Table 8.6 Background information related to the Structured Meeting

Date and Duration	14/10/2011, approximately 65 minutes with four maintenance staff
Place	XX Company
Conductor	The PhD researcher
Target	Maintenance staff from the After-sales Service Department
Purpose	• To discover the life span of the XX machine • To double check whether the machine failure trend predicted by the XX maintenance staff would coincide with the one generated from the cost model • To check whether the estimated values generated from the engineering service cost model were representative • To estimate the costs of providing service contracts at different lengths

Method for Structured Meeting (Validation and Extension Scenario – maintenance staff):

Experts' opinion was the main technique used in this meeting. The researcher acted as a non-participant observer, watching and listening during the discussion section. The researcher was to provide feedback to maintenance staff if they had enquiries as well as to ensure they discussed within the topic.

In addition, the discussion was assisted with an overview presentation. The staff were then handed a hard copy of the Validation and Extension Scenario and a blank table to be completed with expected failure rates (Appendix D). A completed table is shown in Table 9.3.

Structured Meeting –Validation and Extension Scenario – Estimated failure rates and predicted costs

Although the target of this meeting was to ascertain the cost for servicing 100 machines at different service contract lengths, it would be more appropriate to ask maintenance staff about the machine failure rate rather than the engineering services costs. Because the respondents were experts from the After-sales Service Department, they had experience and knowledge on providing engineering services to 100 machines for different customers in the past years. Moreover, as most of the engineering services provided to XX customers were free of charge, maintenance staff would be more familiar with machine failure rates and types of failures rather than the engineering services costs. Therefore, the machine failure rate for 100 machines per year was estimated. Based on experts' estimations of the failure rates, the costs for providing engineering service contract in different contract lengths were then calculated and analysed.

Overall, the outcomes of this structured meeting achieved the purpose i.e. to estimate the failure rate for 100 machines over a 15-year period. The results of the experts' opinions are summarised in Table 8.7.

Table 8.7 The estimated machine failure rate by four maintenance staff

T= Contr-act length (years)	What is the machine failure rate for 100 machines per year?															Explain how you obtain this value
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	
1	200%						-	-	-	-	-	-	-	-	-	Mainly based on experience
3	200%	110%	40%					-	-	-	-	-	-	-	-	
5	200%	110%	40%	15%	5%	-	-	-	-	-	-	-	-	-	-	
7	200%	110%	40%	15%	5%	2%	0.7%	-	-	-	-	-	-	-	-	
9	200%	110%	40%	15%	5%	2%	0.7%	0.1%	2%	-	-	-	-	-	-	
11	200%	110%	40%	15%	5%	2%	0.7%	0.1%	2%	5%	12%	-	-	-	-	
13	200%	110%	40%	15%	5%	2%	0.7%	0.1%	2%	5%	12%	25%	50%	-	-	
15	200%	110%	40%	15%	5%	2%	0.7%	0.1%	2%	5%	12%	25%	50%	75%	100%	

Table 8.7 depicts the after sales expert estimates of the machine failure rate for 100 machines at different engineering service contract lengths. From the data gathered, it was found that for a one year contract, a 200% machine failure rate for 100 machines during their first year in-operation, were estimated. If it was a three-year contract, the machines breakdown frequency was the same in the first year of operation, reducing to 110% and 40% in their second and third year of operation respectively. In contrast, if a fifteen-year contract was proposed, the machine failure rate was initially as high as 200% and this continued to decrease dramatically until the ninth in-operation year. It was noted that the failure rates were 0.7% and 0.1% during the seventh and eighth in-operation years respectively. These failure rates were predicted less than 1% because the maintenance staff stated that the customers undertook self-repair.

Regardless of the length of the engineering service contract, the maintenance staff suggested that the chance of failure of 100 machines within a particular operation year might be consistent. Hence, a complete set of machine failure rate was analysed based on a fifteen-year engineering service contract.

As the engineering services cost model is created based on eight years of data, the first eight years of machine failure rate predicted by the experts were used to validate the cost model. More importantly, fifteenth years of machine failure rate predicted by the experts were used to extend the engineering services cost model, which is described in Section 8.5.

In Chapter 7, the trend and the performance factor for predicting the overall machine failure rate were established. In this section, by adapting the same process for the Validation and Extension Scenario, the pattern of machine failure over an eight-year service contract predicted by maintenance staff was identified and analysed.

Based on the Validation and Extension Scenario and Table 8.7, the total number of machines and total number of machine failures for an eight-year engineering service contract are presented in Table 8.8. The maintenance experts predicted that the 100 machines from the Validation and Extension scenario had 200 failures in their first operation year, 100 failures in the second operation year, and so on. The number of failures is calculated as a product of the total number of in-operation machines multiplied by the machine failure rate for the j^{th} year, which is presented in Table 8.8. The number of failures can then be used to estimate the cost for engineering services.

Table 8.8 Number of Machines in Operation for at Least *i* Years; Machine Failure Rate and Number of Machine Failures in the *j*th Year of Operation

Years in operation (i)	*Number of in-operation machines (N_i)*	*Year of operation (j)*	*Machine failure rate predicted by experts (ω_j)*	*Number of machine failures predicted by experts* ($E_{f_j} = \omega_j \times N_i$)
1	100	1	*200%*	*200*
2	100	2	*110%*	*110*
3	100	3	*40%*	*40*
4	100	4	*15%*	*15*
5	100	5	*5%*	*5*
6	100	6	*2%*	*2*
7	100	7	*0.7%*	*0.7*
8	100	8	*0.1%*	*0.1*

Using the results summarised in Table 8.8, in terms of providing an eight-year engineering service contract to 100 XX machines, the relationship between machine failure rate and the number of years in operation is presented in Figure 8.3. It depicts that approximately 200% of the 100 machines failed during their first year in-operation. The failure rate reduced to 110% and 40% for the same sets of machines in their second and third year in-operation respectively. After the machine had been in-operation for three years, the machine breakdown frequency reduced dramatically from the fourth to the eighth year.

Calculate the cost of providing engineering service contracts based on experts opinions

Based on the failure rate predicted by the maintenance staff (Table 8.7), the total cost variables for servicing 100 machines to 100 different customers from one to eight in-operation years were then calculated. The average costs of providing phone service (Caverage_pj), spare parts service (Csps_mf) and on-site repair service (Caverage_6j) were calculated based on the CERs established in Chapter 7. By applying the same principle, the estimated costs based on the expert opinions are summarised in Table 8.9. Utilising the opinions of the XX financial staff, it was assumed that the total overhead cost is 5% of the total engineering services cost each year. Hence, the total engineering services costs for providing 100 machines (Caverage_es) is the sum of these three service cost variables multiplied by 5%, which are presented in Table 8.10.

Table 8.9 Engineering Services Cost Variables for 100 Machines in the jth Year of Operation

Year of operation (j)	***Machine failure rate predicted by experts*** (ω_j)	***Number of machine failures predicted by experts*** $(E_{f_j} = \omega_j \times N_i)$	***Total phone costs*** **Caverage_pj = CER_1 = 2002.92* Efj**	***Total spare part costs*** **Csps_mf = CER_2 = 39674.77*Ef**	***Total on-site repair costs*** **Caverage_6j = CER_3 = 28644.78* Efj)**
1	200%	200	400,384	7,934,954	5,728,956
2	110%	110	220,211	4,364,225	3,150,926
3	40%	40	80,077	1,586,991	1,145,791
4	15%	15	30,029	595,122	429,672
5	5%	5	10,010	198,374	143,224
6	2%	2	4,004	79,350	57,290
7	0.7%	0.7	1,401	27,772	20,051
8	0.1%	0.1	200	3,967	2,864

Table 8.10 Total Cost for servicing 100 Machines in the jth Year of Operation

Year of operation (j)	**Caverage_es= (Caverage_pj+ Csps_mf+ Caverage_6j) ×(1+5%)**
1	14,767,509
2	8,122,130
3	2,953,502
4	1,107,563
5	369,188
6	147,675
7	51,686
8	7,384

Based on the estimated cost for each operation year in Table 8.10, the costs of providing different lengths of engineering service contracts (*T*) were determined. This is calculated as a yearly average over the contract period with contract periods of one, three, five or seven years, as depicted in Table 8.11.

Table 8.11 The Per Year Cost of Servicing 100 Machines for a One, Three, Five, Seven-Year Contract

T	Mathematical relationship	Per-year cost of servicing 100 machines for *T* years (Millions)
1	C_1	14.8
3	$\frac{C_1 + C_2 + C_3}{3} = \frac{1}{T}\sum_{j=1}^{T} C_j$	8.6
5	$= \frac{1}{T}\sum_{j=1}^{T} C_j$	5.5
7	$= \frac{1}{T}\sum_{j=1}^{T} C_j$	4.0

The cost for a one-year engineering service contract for the 100 machines was estimated at RMB 14.8M, whereas the per-year cost reduced approximately by 42% for a three-year contract. Further cost reductions were calculated for a five-year contract (RMB 5.5M) and a seven-year contract (RMB 4M).

Validation and Extension Scenario uitilised expert opinions to ascertain what the expected failure rates would be. The next scenario (Validation Scenario) investigated the cost of providing engineering services using the engineering services cost model. The failure rates used in the cost model were based on the analysis of eight years of historical data obtained form the XX Company.

8.4.2 Validation Scenario – cost model

Validation Scenario:

We wish to sell 100 XX machines from the same production line. Each machine is to be sold to a different customer in Mainland China. These customers are requesting that we enter into an engineering service contract with them. The options are different contract lengths--one, three, five, and seven years. What are the costs for providing such a service at different contract lengths?

The need for Validation Scenario – provision of CERs when there is no historical data

As the engineering service cost model is validated to estimate the costs for providing engineering service to XX customers for eight in-operation years, Validation Scenario was similar to Validation and Extension Scenario except the engineering service contract lengths and test target. Based on Validation Scenario, the model was used to predict the costs of providing one, three, five, and seven years engineering service contract. This means that the contract of nine, eleven, thirteen and fifteen years available in the Validation and Extension Scenario were no longer presented.

Moreover, although the Validation and Extension Scenario did not have the same test target as the Validation Scenario – i.e. the aim was to ascertain the failure rates for a 15-year period, the costs of providing the engineering service contract could be derived from the results generated from the Validation and Extension Scenario. Hence, the main goal of these two scenarios was similar, which was to find out the costs for providing service contracts by utilising expert opinions and the cost model respectively. Consequently, the costs for providing services to 100 machines predicted by the maintenance staff and the engineering services cost model were compared based on Validation Scenario, i.e. for a 1, 3, 5 and 7-year service contract. The service cost comparison between these two scenarios were then examined and analysed.

Calculate the cost of providing engineering service contract based on the cost model

Using the findings from the historical data collected from the XX Company (refer to Chapter 7), the machine failure rate and total number of machine failures for Validation Scenario are presented in Table 8.12. The 100 machines were used to examine the machine failure rate. The expected machine failure rate is calculated based on Equation 7.1 established in Chapter 7, which is $\lambda_j = 4.1382e^{-0.6269j}$, where λ_j is expected machine failure rate in the j^{th} year. Moreover, the number of failures each year (N_{fj}) is calculated as the number of in-operation machine (N_i) multiplied by the corresponding failure rate.

Table 8.12 Machine Failure Rate and Number of Failures in the jth Year of Service

Year in service	Expected machine failure rate	Expected number of failures per year
j	$\lambda_j = 4.1382e^{-0.6269j}$ (Chapter 7: Equation 7.1)	$N_{fj} = N_i * \lambda_j$ (Chapter 7: Equation 7.2)
1	221%	221
2	118%	118
3	63%	63
4	34%	34
5	18%	18
6	10%	10
7	5%	5
8	3%	3

Based on Table 8.12, the machine failure rates are presented in Figure 8.3. A 221% machine failure rate occurred on 100 machines during their first year in-operation, which means on average, every machine had more than two failures during its first year in operation. However, in year two this reduced significantly to around 118% based on the same sample of machines. During the third and fourth in-operation years, the machines failed less frequently. After the machine had been in operation for more than four years, the failure rates reduced dramatically to less than 10%. Therefore, in general, within the eight in- operation years, the longer the machine had been in service the less likely it was to fail.

This particular pattern coincided with the first eight in-operation years of machine failure rate trend predicted by experienced maintenance staff (Figure 8.5). Although the data might vary slightly between Figure 8.3 and Figure 8.5, the patterns of machine failure against in-operation years predicted by the cost model and by the maintenance experts were similar. Both trends follow the common failure pattern for repairable components of a product, which is the earlier stage of a bathtub model. Hence, the engineering services cost model was validated by knowledgeable experts as well as by historical data.

Figure 8.3 The relationship between machine failure rate and years in-operation (1-8yrs)

Moreover, in terms of model estimation, the average costs of providing phone service (Caverage_pj), spare parts service (Csps_mf) and on-site repair service (Caverage_6j) were calculated based on the CERs established in Chapter 7. Hence, the total engineering services cost for providing 100 machines (Caverage_es) is the sum of these three service cost variables, which is presented in Table 8.13.

Table 8.13 Total costs variables for servicing 100 machines in the *j*th year of operation

j	Total expected phone costs	Total expected spare part costs	Total expected on-site repair costs	Total expected engineering services cost
	Caverage_pj = CER_1 = 2002.92* N_{fj}	**Csps_mf = CER_2 = 39674.77* N_{fj}**	**Caverage_6j = CER_3 = 28644.78* N_{fj}**	**Caverage_es = C_{es} = (CER_1+ CER_2+ CER_3)×(1+5%)**
1	442,587	8,771,355	6,332,829	16,324,110
2	236,450	4,686,056	3,383,285	8,721,080
3	126,322	2,503,504	1,807,504	4,659,197
4	67,487	1,337,485	965,651	2,489,155
5	36,055	714,545	515,895	1,329,819
6	19,262	381,743	275,614	710,450
7	10,291	203,944	147,246	379,555
8	5,498	108,956	78,665	202,775

Based on these cost estimates for each operation year, the costs of providing different lengths of engineering service contracts (*T*) were determined. This is calculated as a yearly average over the contract period with contract periods of one, three, five or seven years, as depicted in Table 8.14. CERs 1-3 and C_{es} used in this table were defined in Chapter 7.

Table 8.14 The Per Year Cost of Servicing 100 Machines

T	Mathematical relationship	Per-year cost of servicing 100 machines for *T* years (Millions)
1	C_1	16.3
3	$\frac{C_1+C_2+C_3}{3} = \frac{1}{T}\sum_{j=1}^{T} C_j$	9.9
5	$= \frac{1}{T}\sum_{j=1}^{T} C_j$	6.7
7	$= \frac{1}{T}\sum_{j=1}^{T} C_j$	4.9

The cost for a one-year engineering service contract for the 100 machines was estimated at RMB 16.3M, whereas the per-year cost reduced approximately by 39% for a three-year contract. Further cost reductions were calculated for a five-year and a seven-year contract. The costs of providing a five year contract was estimated as RMB 6.7M per year, whereas, the costs for a seven-year contract was estimated as RMB 4.9M per year. In general, the longer the engineering service contract, the yearly price to the customer reduces. This particular pattern matched with the trend derived from maintenance staff's viewpoints within the first eight in-operation years (Table 8.4).

8.4.3 Cost comparison between the cost model and the experts

A comparison of the annual average costs for providing engineering services costs for 100 machines was made between the experienced maintenance staff and the cost model (Tables 8.11 and 8.14). This comparison is presented in Figure 8.4. The solid line depicts the cost values predicted by the engineering services cost model, whereas the dashed line shows the cost values derived from experienced maintenance staff. In general the experts underestimated the costs of service provision (in this case through underestimating the expected failure rates). This aligns with the research by Jager and Bertsche (2004).

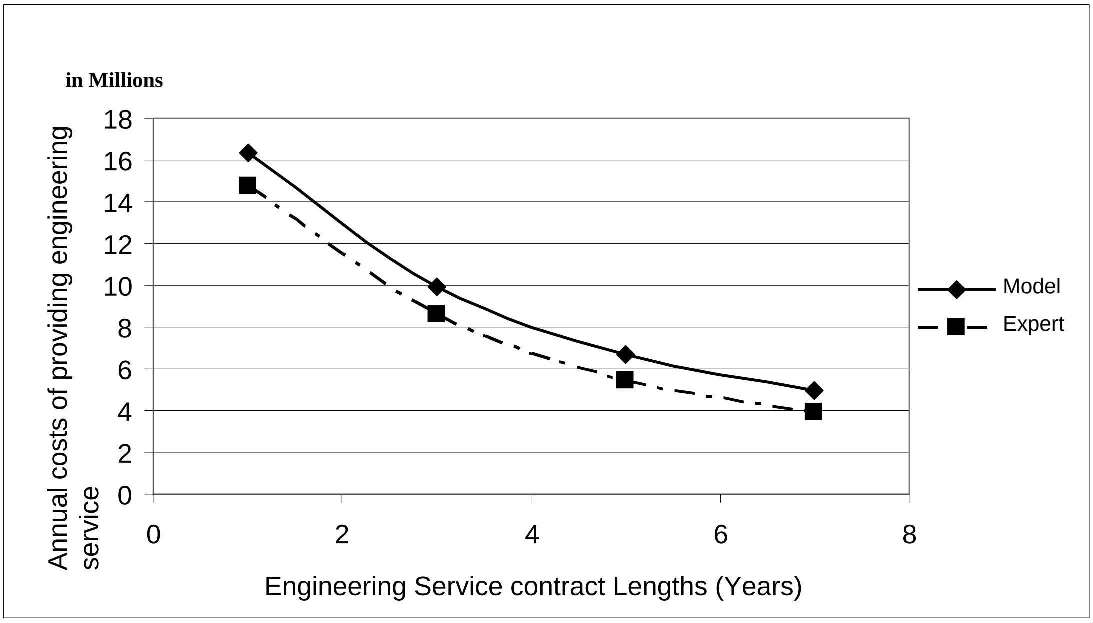

Figure 8.4 Model Estimation versus Experts Estimation

From Figure 8.4, the statement that the longer the engineering service contract, the lower the yearly price to customer to provide such services per year is valid for both cases within the eight in-operation years. Both trends predicted by the experts and the cost model initially had a high cost for providing a one-year contract, and this cost reduced significantly as the contract length extended towards the eighth year. In general, the cost of providing an engineering service contract over a number of years predicted by the model was around 20% more expensive than the costs for providing the same contract predicted by the maintenance staff. The maximum cost difference was 26% for a seven-year contract and the minimum cost difference was 11% for a one-year contract.

The engineering services cost model was validated by experts as well as by historical data. More importantly, the accuracy of the cost outputs generated from the cost model were examined and compared with expert opinions. The findings showed that the cost model and the expert opinions had a similar behaviour pattern. Although there was variance between the two sets of results, this was consistent at around 20% and reflected what has been presented in the literature (Jager and Bertsche, 2004).

8.5 Step 4: Extension of the Cost Model – Expert Opinions (15 years)

This section describes how the engineering services cost model was extended to enable the modelling of service contracts for up to 15 years by utilising expert opinions. Based on the Validation and Extension Scenario and Table 8.7, the total number of machines and total number of machine failures for a fifteen-year engineering service contract are presented in Table 8.15. The maintenance experts predicted that the 100 machines from Validation and Extension Scenario had 200 failures in their first operation year, 100 failures in the second operation year, and so on. The number of failures is calculated as a product of the total number of in-operation machines multiplied by the machine failure rate for the j^{th} year, which is presented in Table 8.15. The number of failures can then be used to estimate the cost for engineering services.

Table 8.15 Number of Machines in Operation for at Least i Years; Machine Failure Rate and Number of Machine Failures in the jth Year of Operation (15 years)

Years in operation (i)	*Number of in-operation machines (N_i)*	*Year of operation (j)*	*Machine failure rate predicted by experts (ω_j)*	*Number of machine failures predicted by experts ($E_{f_j} = \omega_j \times N_i$)*
1	100	1	*200%*	*200*
2	100	2	*110%*	*110*
3	100	3	*40%*	*40*
4	100	4	*15%*	*15*
5	100	5	*5%*	*5*
6	100	6	*2%*	*2*
7	100	7	*0.7%*	*0.7*
8	100	8	*0.1%*	*0.1*
9	100	9	*2%*	*2*
10	100	10	*5%*	*5*
11	100	11	*12%*	*12*
12	100	12	*25%*	*25*
13	100	13	*50%*	*50*
14	100	14	*75%*	*75*
15	100	15	*100%*	*100*

Using the results summarised in Table 8.15, in terms of providing a fifteen-year engineering service contract to 100 XX machines, the relationship between machine failure rate and the number of years in operation is presented in Figure 8.5. It depicts that approximately 200% of the 100 machines failed during their first year in-operation. The failure rate reduced to 110% and 40% for the same sets of machines in their second and third year in-operation respectively. After the machine had been in-operation for three years, the machine breakdown frequency reduced dramatically from the fourth to the eighth year until the ninth year in-operation. In the ninth year the machine failure rate started to increase. Therefore, the ninth operation year seemed to be the turning point where the machine started to fail more frequently. During the twelfth in-operation year, maintenance staff suggested that a quarter of the 100 machines might have failures, which indicated the machines started to deteriorate. This deterioration became worse for later operation years. During the machine's fifteen-year in-operation, the machine failure rate towards the end of the fifteen-year engineering service contract was estimated to be 100%, i.e. each machine would expect to have at least one breakdown. This is nearly as high as it initially started at the second in-operation year of the service cycle.

This particular pattern of machine failures predicted by the experts' matches the failure pattern for repairable components of a product, which is the bathtub failure model (O'Connor, 1991; Dhillon, 2010). Based on maintenance staff's viewpoints, the following section calculated the costs of providing engineering services to 100 machines at different contract lengths.

Figure 8.5 The relationship between machine failure rate and years in-operation (Expert opinions)

Calculate the cost of providing engineering service contract based on experts opinions

Based on the failure rate predicted by the maintenance staff (Table 8.7), the total cost variables for servicing 100 machines to 100 different customers from one to fifteen in-operation years were then calculated. The average costs of providing phone services (Caverage_pj), spare parts services (Csps_mf) and on-site repair services (Caverage_6j) were calculated based on the CERs established in Chapter 7. By applying the same principle, the estimated costs based on the expert opinions are summarised in Table 8.16. Based on XX financial staff opinions, it was assumed that the total overhead cost is 5% of the total engineering services cost each year. Hence, the total engineering services costs for providing 100 machines (Caverage_es) is the sum of these three service cost variables multiplied by 5%, which are presented in Table 8.17.

Table 8.16 Engineering Services Cost Variables for 100 Machines in the jth Year of Operation (15 years)

Year of operation (*j*)	*Machine failure rate predicted by experts* (ω_j)	*Number of machine failures predicted by experts* ($E_{f_j} = \omega_j \times N_i$)	*Total phone costs* Caverage_pj = CER_1 = 2002.92* Efj	*Total spare part costs* Csps_mf = CER_2 = 39674.77*Ef	*Total on-site repair costs* Caverage_6j = CER_3 = 28644.78* Efj)
1	200%	200	400,384	7,934,954	5,728,956
2	110%	110	220,211	4,364,225	3,150,926
3	40%	40	80,077	1,586,991	1,145,791
4	15%	15	30,029	595,122	429,672
5	5%	5	10,010	198,374	143,224
6	2%	2	4,004	79,350	57,290
7	0.7%	0.7	1,401	27,772	20,051
8	0.1%	0.1	200	3,967	2,864
9	2.%	2	4,004	79,350	57,290
10	5%	5	10,010	198,374	143,224
11	12%	12	24,023	476,097	343,737
12	25%	25	50,048	991,869	716,120
13	50%	50	100,096	1,983,739	1,432,239
14	75%	75	150,144	2,975,608	2,148,359
15	100%	100	200,192	3,967,477	2,864,478

Table 8.17 Total Cost for servicing 100 Machines in the jth Year of Operation (15 years)

Year of operation (j)	**Caverage_es= (Caverage_pj+ Csps_mf+ Caverage_6j) ×(1+5%)**
1	14,767,509
2	8,122,130
3	2,953,502
4	1,107,563
5	369,188
6	147,675
7	51,686
8	7,384
9	147,675
10	369,188
11	886,051
12	1,845,939
13	3,691,877
14	5,537,816
15	7,383,754

Based on the estimated cost for each operation year in Table 8.17, the costs of providing different lengths of engineering service contracts (T) were determined. This is calculated as a yearly average over the contract period with contract periods of one, three, five or seven, nine, eleven, thirteen, and fifteen years, as depicted in Table 8.18.

Table 8.18 The Per Year Cost of Servicing 100 Machines for a One, Three, Five, Seven, Nine, Eleven, Thirteen, and Fifteen-Year Contract

T	**Mathematical relationship**	**Per-year cost of servicing 100 machines for *T* years (Millions)**
1	C_1	14.8
3	$\frac{C_1+C_2+C_3}{3}=\frac{1}{T}\sum_{j=1}^{T}C_j$	8.6
5	$=\frac{1}{T}\sum_{j=1}^{T}C_j$	5.5
7	$=\frac{1}{T}\sum_{j=1}^{T}C_j$	3.9
9	$=\frac{1}{T}\sum_{j=1}^{T}C_j$	3.1
11	$=\frac{1}{T}\sum_{j=1}^{T}C_j$	2.6
13	$=\frac{1}{T}\sum_{j=1}^{T}C_j$	2.7
15	$=\frac{1}{T}\sum_{j=1}^{T}C_j$	3.2

The cost for a one-year engineering service contract for the 100 machines was estimated at RMB 14.8M, whereas the per-year cost reduced approximately by 42% for a three-year contract. Further cost reductions were calculated for a five-year contract (RMB 5.5M) and a seven-year contract (RMB 3.9M) and so on.

It was found that the ninth operation year was the turning point, where the machine failure rates began to increase as depicted by a typical bathtub failure behavior. Before this point, the longer the engineering service contract, results in the customer paying a lower yearly price, as the costs are balanced over the contract period. However, after year nine exceptions occurred, which were the costs for providing a thirteen and fifteen year contract. In these cases the overall yearly cost needed to increase to reflect the upturn of the bathtub failure model.

When 50% of machines were predicted to fail in the thirteenth in-service year, the costs of providing a thirteen-year contract was slightly higher than the costs of providing an eleven-year contract. Similarly, when 100% of machine failure rates were predicted in the fifteenth in-operation year, the average costs of providing a fifteen-year contract was estimated at RMB 3.2M, which was approximately 20% more than the costs of providing an eleven and thirteen year contract.

8.6 Summary

In this chapter, the engineering services cost model was validated and extended by following four steps. First, by applying the technique of face validity, the concept of the cost model was validated by two groups of experienced staff from the XX Company. Second, the cost model was validated by splitting the machine data into mechanical and electrical data. Third, the cost model was validated based on 1-8 years of expert opinions. Finally, the cost model was extended to estimate the engineering services cost for up to 15 years based on expert opinions. This final extension phase showed that the bathtub failure model was appropriate for use in predicting the cost of engineering services.

In the next chapter, service scenarios to illustrate how the validated and extended cost model can be used to assist with the pricing of contracts are tested and analysed.

Chapter 9 Scenarios Test and Analysis

Chapter 8 described how the cost model was validated and extended by using addition data and expert opinions. In this chapter, further analysis of the cost model using '*what if?*' scenarios is presented. Three scenarios are described (Scenarios 1-3). Scenario 1 is utilised to propose how to price engineering service contract based on 1, 3, 5, 7, 9, 11, 13 and 15 years in-operation. Scenarios 2 and 3 are used as an example to show how to allocate on-site staff based on the number of machines in-operation. These scenarios are summarised in Tables 9.1, 9.2 and 9.3. The scenario number, the way it was tested and reasons are presented. The aim of this chapter is to demonstrate how the model could be used to estimate the cost for engineering services.

Table 9.1 Scenario 1

Scenario 1: Estimating the machine failure rates of 100 machines for a single customer over different in-service contract lengths (between 1 and 15 years)		
Objectives	**Reasons Tested**	**Method of Analysis**
1. Acquire data to identify CERs for machines greater than 8 years old and from this ascertain the key behavior points of the bathtub model. 2. Using expert opinions, estimate the costs of proving in-service contracts.	1. Utilising expert opinions, to ascertain the failure pattern of 100 machines sold to a single customer.	1. Expert opinions (staff with 10-15 years experience of machine breakdowns). 2. Based on expert opinions, predict the costs of providing in-service contracts to a single customer. 3. Comparison of expert opinion and cost model predictions.

Table 9.2 Scenario 2

Scenario 2: To estimate the costs of providing a one-year engineering service contract of 100 machines to a single customer by *sending* two maintenance staff to be based at the customer's company.		
Objectives	**Reasons Tested**	**Method of Analysis**
1. Based on scenario 2, the costs of providing a one-year engineering service contract were estimated.	1. To use as an example to show how to allocate on-site staff based on the number of in-operation machines	1. Engineering service cost model prediction. 2. Comparison of cost model prediction between scenario 2 and 3.

Table 9.3 Scenario 3

Scenario 3: To estimate the costs of providing a one year engineering service contract of 100 machines to a single customer *without sending* two maintenance staff to customer's company.		
Objectives	**Reasons Tested**	**Method of Analysis**
1. Based on scenario 3, the costs of providing a one-year engineering service contract were estimated.	1. To use as an example to show how to allocate on-site staff based on the number of in-operation machines	1. Engineering service cost model prediction. 2. Comparison of cost model prediction between scenario 2 and 3.

The next sections in this chapter describe how these scenarios were evaluated along with a more detailed description of why each scenario was investigated. The advantages and disadvantages of the scenarios being modelled are also presented. Conclusions from the scenario modelling are then given.

9.1 Scenario 1 – Single site – 100 machines

This section described how expert opinions were obtained from Scenario 1. The reasons for conducting Scenario 1 were justified. It then presented how Scenarios 1 was tested. More importantly, the outcome from Scenario 1 was discussed. For this purpose Scenario 1 was as follows.

Scenario 1:
We wish to sell 100 XX machines from the same production line. 100 machines were sold to the same customer in Mainland China. The customer is requesting that we enter into engineering service contract with them. The options are different contract lengths – one, three, five, seven, nine, eleven, thirteen and fifteen years. What are the machine failure rates for 100 machines per year at different contract lengths?

9.1.1 Purpose of conducting Scenario 1

From Chapter 1, it was identified that there is a need for companies to understand the costs of providing engineering services. However this is one of the key challenges for both industry and academia. For example, in the defence sector a key challenge is to estimate the engineering services cost for military provision (Mathaisel et al., 2009). Gray also highlighted where projects had over-run and gone over budget for defence products. This however, is not just an issue within the defence sector but also within other domains such as in construction. Patel (2011) found that in Tanzania where the service provider was responsible for maintaining roads they underestimated the cost of the in-operation support by 50%. The construction company could minimise losses and gain more profits by providing engineering service contract based on different contract length. For instance, the shorter the contract lengths, the more expensive the annual price would be based on the results shown in Chapter 8. Moreover, if a particular road requires more frequent maintenance, it might be cost-effective to allocate a maintenance staff to stay close-by. Hence, the cost and time for travelling are minimised and the road might be better served by providing more preventative maintenance. These strategies may help companies to provide better engineering services and obtain profits in a long term.

Meanwhile, a review of the domain has found that very few cost estimating tools model the cost for engineering services (Cheung et al., 2009a).

To fill in the gaps of engineering services costing in both industry and academia, Scenario 1 was conducted with two main proposes. One was to propose how to price an engineering service contract to a group of identical machines for a single customer based on the contract lengths. The other was to propose how to allocate on-site staff based on the number of machines in-operation. Scenario 1 utilised expert opinions to predict the likely failure rates.

9.1.2 Structured Meeting – Likelihood of machine breakdowns

Within this section, the background and methods of this meeting are introduced. A general discussion and analysis about the outcomes of the meeting are also presented. Table 9.4 summarises the general background of the meeting. It includes meeting information related to the date, duration, place, conductor, target, and purpose.

Table 9.4 The background information related to the Structured Meeting

Date and Duration	21/10/2011, approximately 55 minutes with four maintenance staff
Place	XX Company
Conductor	The PhD researcher
Target	Maintenance staff from the After-sales Service Department
Purpose	• To ask maintenance staff viewpoints on providing a long term engineering service contract based on Scenario 1 • To compare Scenario 1 with Validation and Extension Scenario, and identify any similarities and differences • To estimate the service costs of providing 100 machines to a single customer • To propose service solutions for Scenario 1

Method for Structured Meeting:

The method used in the structured meeting for Validation and Extension Scenario (Chapter 8) was applied in this meeting. The discussion was assisted with an overview introduction. The staff were then handed a hard copy of the Scenario 1 during the discussion section. (Appendix E).

Outcome for Structured Meeting:

As the maintenance staff hardly had experience of servicing numerous machines to a single customer, they could not estimate the exact values of machine failure rate for Scenario 1. However, based on their extensive experience, all of them agreed that the machine failure rate for 100 machines sold to a single customer were likely to follow a similar pattern for the set of machines sold to different customers. This was mainly because the general failure pattern for a repairable product was consistent, following a bathtub failure model (O'Connor, 1991; Dhillon, 2010).

Furthermore, based on maintenance staff's past experience of servicing as many as four identical machines from the same customer, they suggested that the overall machine failure rate for 100 machines purchased by one user may be around 50% less than the predictions they made in the previous meeting which was to estimate the failure rate for these machines sold to different customers (Validation and Extension Scenario). Hence the costs of providing service for a single customer may be less than the costs of providing the same service for 100 customers.

This prediction was drawn mainly based on the following reasons.

a. When the 100 machines were sold to the same customer, it would be easier to prevent common failures of machine breakdown. This could be achieved when one failure occurs in machine 1, the XX maintenance staff would fix the problem and educate the operators on how to control, repair and maintain the machine properly to prevent similar failures to machine 2, 3, 4 and so on.

b. As the 100 machines are from the same supplier, the more experienced and knowledgeable operators would guide and assist the less experienced operators. Hence the overall level of operators from a single company would be better than operators from different companies. Since the experience and knowledge of the operators could have a direct impact on the performance of the machines, the overall machine breakdown for 100 machines sold to one company may be less frequent than the individual machine breakdowns for machines sold to different companies.

c. When the 100 machines were located in 100 different places, there were less possibility that these machines would fail at the same time due to numerous uncertainties, such as the level of operators, working environment, how the machine integrate with the whole production line, and the type of end products. If more than one machine failed simultaneously at firms located in different part of China, the costs of labour and travelling could be high. The costs of offering an on-site visit for machines in a single company would be more economic and effective.

d. In the XX Company, when machines were randomly sold to different customers across Mainland China, it was comparably difficult to find out the common failure parts and their causes. Machine A from customer A may have a failure part due to an operator controlling the machine incorrectly, or machine B from customer B where the breakdown was due to the machine being overloaded. There are more uncertainties and risks when providing a spare part service to many different customers. To face the high level of uncertainties and risks, each year XX Company had to spend a large proportion of expenses on stocking different components in order to satisfy their customers. In contrast, the level of uncertainties and risks associated with a single customer are lower. For example, considering Scenario (1), the XX machines were likely to be operated and maintained similarly; how the XX machines were integrated with the production line were similar; the working environment of XX machines were similar. In Scenario (1), common failure parts and root causes might be identified earlier. Therefore, it could be easier to keep records on the common failures and failure parts, and hence reduce the level of storage. Based on the analysis, the costs for providing spare parts service for 100 machines in a single location would be relatively cheaper.

e. Similarly, the uncertainties and risks with a single customer might enable the common failures to be easier to identify, with the maintenance staff being more familiar with the customer. It might be worthwhile to have one XX maintenance staff being responsible for the phone service to improve the relationship with the customer. At present every XX maintenance staff deal with the phone service when they are available. Meanwhile, the customer's company could also delegate an operator who was responsible for reporting technical problems related to the XX machine. This proposal would enable the XX staff and the operators dealing with the phone service to develop a high quality relationship for a long-term service contract, which may improve problem solving. Moreover, the phone calls could be recorded for training and monitoring purposes. This may also help the XX Company to provide a better phone service, as well as minimise the unnecessary social or personal topics. Hence, it might be more cost effective to provide a phone service to a single customer than providing such service to 100 customers.

9.2 How to price engineering service contract

This section proposes how to price engineering service contract for 100 machines on a single site based on different contract length. The price of engineering service contract is varied based on 1, 3, 5, 7, 9, 11, 13 and 15 years contract lengths.

Calculate the cost of providing engineering service contract based on experts opinions

In Scenario 1 (Chapter 9), the failure rate for 100 machines sold to a single customer over a 15-year period was predicted as 50% less than failure rate in the Validation and Extension Scenario (Chapter 8). As the cost of providing engineering services is dependent on the machine failure rate, the cost for servicing 100 machines on a single site is around 50% less than the cost for servicing 100 machines on 100 different sites (Validation and Extension Scenario). Hence, the per-year cost of servicing 100 machines to a single site is estimated as half of the yearly cost of servicing the same number of machines to 100 different sites shown in Table 8.18 (Chapter 8). This is presented in Table 9.5.

Table 9.5 The Per Year Cost of Servicing 100 Machines on a Single Site for a One, Three, Five, Seven, Nine, Eleven, Thirteen, and Fifteen-Year Contract

T	Per-year cost of servicing 100 machines to 100 different sites for *T* years (Millions)	Per-year cost of servicing 100 machines on a single site for *T* years (Millions)
1	14.8	7.4
3	8.6	4.3
5	5.5	2.8
7	3.9	2.0
9	3.1	1.6
11	2.6	1.3
13	2.7	1.4
15	3.2	1.6

The cost for a one-year engineering service contract for the 100 machines on a single site was estimated at RMB 7.4M, whereas the per-year cost reduced approximately by 42% for a three-year contract. Further cost reductions were calculated for a five-year contract (RMB 2.8M) and a seven-year contract (RMB 2M) and so on.

It was found that the ninth operation year was the turning point, where the machine failure rates began to increase as depicted by bathtub failure behaviour. Before this point, the longer the engineering service contract, the less the yearly price to the customer to provide such services per year. After this point, exceptions occurred, which were the costs for providing a thirteen and fifteen year contract. In these cases the overall yearly cost needed to increase to reflect the upturn of the bathtub failure.

9.3 Cost Model Analysis on allocating on-site staff (single site)

This section describes how to allocate on-site staff based on the number of machines in-operation on a single site. Scenarios 2 and 3 are used as an example to demonstrate how to allocate on-site staff based on 100 machines in-operation. The same approach could be used to determine where the cost effective threshold is for allocating staff to a customer site.

9.3.1 Scenarios 2 and 3

According to the maintenance staff's opinions, the overall machine failure rate for 100 machines supplied to one customer may be 50% less than that for 100 customers

(Section 9.1.2). Based on this assumption, Scenario 2 was tested by the engineering service cost model. Scenario 2 was designed for a one-year service contract, as the machine failure rate at the first in-service year was generally much higher than the rest of the years.

Scenario 2:
We wish to sell 100 XX machines from the same production line to a single customer in Mainland China. The customer is requesting that we enter into a one-year engineering service contract with them. It was assumed that the machine failure rate in Scenario 2 was around 50% less than the Validation and Extension Scenario. Hence, is it worth XX Company to dedicate two maintenance staff (1 mechanical and 1 electrical) to stay on-site at the customer's company?

In order to test Scenario 2, Scenario 3 was established.

Scenario 3:
We wish to sell 100 XX machines from the same production line. 100 machines were sold to the same customer in Mainland China. The customer is requesting that we enter into a one-year engineering service contract with them. It was assumed that the machine failure rate in Scenario 3 was around 50% less than the Validation and Extension Scenario.

Technical problems related to these machines were solved over the phone as priority. If the problem could not be solved over the phone, on-site repair visits were arranged to customers companies. Meanwhile, if replacing a spare part could solve the problem, spare part services were provided. What are the costs for providing a one-year service contract to 100 machines?

9.3.2 The Cost Modelling based on Scenarios 2 and 3

This section described how scenario 2 was tested by the engineering service cost model based on the following three steps. 1) Based on Scenario 3, the costs of providing service to 100 machines for one customer were estimated. 2) Using Scenario 2, the saving cost for allocating two staff on-site was estimated. 3) By following the same steps in Scenarios 2 and 3, how to allocate on-site staff based on the different number of in-operation machines is calculated and analysed.

Step 1) The costs of servicing 100 machines - Scenario 3

The machine failure rate for servicing 100 machines for one customer for a one-year service contract is calculated as

Failure rate = 200% × 50% = 100% (9.1)

Hence, the number of machine failures = 100% × 100 machines

= 100 failures for a one year contract.

(9.2)

Using CERs 1-3 and C_{es} established in Chapter 7, the costs of providing phone service, spare parts service and on-site repair services are calculated as followed.

Costs of providing phone service
= CER_1
= average phone cost per failure × expected number of failures
= 2002 × N_{f_j}
= 2002 × 100
= RMB 200,200 (9.3)

Costs of providing spare part service
= CER_2
= average spare parts cost per failure × expected number of machine failures
=39,675 × N_{f_j}
= 39675 × 100
= RMB 3,967,500 (9.4)

Costs of providing on-site repair service
= CER_3
= average on-site repair cost per failure × expected number of machine failures
= 28645 × N_{f_j}
= 28645 × 100
= RMB 2,864,500 (9.5)

Therefore, the total costs of proving a one-year engineering service contract
= C_{es}
= (CER_1 +CER_2 + CER_3) × (1+overheads%)
= (200,200+3,967,500+2,864,500) × (1+5%)
= RMB 7.4 (millions) (9.6)

It was found that the total costs of providing a one-year engineering service contract to one customer was RMB 7.4M, which was approximately 55% less than the costs of providing the same contract to 100 customers predicted by the cost model (Validation Scenario). More importantly, it was noted that the costs of providing on-site repair service were much more than the costs of providing phone service or repair part service. However, the values can be used to decide on the most appropriate way of providing the engineering services.

Step 2) The cost savings if two staff are based on-site at the customer's facility - Scenario 2

To reduce the costs of on-site repair service, XX Company was recommended to send two maintenance staff to stay in the customer' company. One was responsible for mechanical failures of the XX machines, whereas the other was in charge of electrical failures. The average costs of on-site repair service included the costs of travelling, accommodation, meals, labour, subsidies for travelling and bonus. The proposal in Scenario 2 means that the costs of travelling, accommodation, and meals could be minimised compared with the costs generated from Scenario 3. However, the costs of subsidies might increase as maintenance staff spent more time on-site. In addition, the costs of labour and bonus remained the same from Scenario 3 because these attributes were constant regardless of the work location. Based on Scenario 2, the costs of providing an on-site repair service with maintenance staff staying on-site for a one year service contact were calculated by following steps a) to e).

Step a) Based on the assumption, 100 failures means these failures could be solved by on-site repair visits. If the maintenance staff stayed on-site, the original costs for travelling could be eliminated. The following calculation is based on the in-service data presented in Table 7.11 and Table 7.13 (Chapter 7). These tables are duplicated here for clarity.

Table 7.11 Total Cost Variables of On-site Repair Service (years 2003-2010)

I_s	C_{tpj}	$C_{aj}+C_{mj}$	C_{sj}	C_{boj}	Clj	Clj_v= Clj×80%×80%
2003	100,000	20,000	21,000	60,000	90,545	57,949
2004	150,000	30,000	42,000	103,000	130,000	83,200
2005	215,500	80,000	70,000	156,000	142,800	91,392
2006	260,000	100,000	82,000	203,000	180,000	115,200
2007	380,000	152,000	110,000	261,000	230,000	147,200
2008	410,000	170,000	150,000	320,000	240,000	153,600
2009	430,000	200,000	180,000	360,000	270,000	172,800
2010	480,000	250,000	220,000	390,000	320,000	204,800

Table 7.13 The Average on-site repair cost per failure in their *Is* Years

Year sold to customer (I_s)	*Total number of machine failures in the I_s year (N_{is})*	*Average on-site repair cost per failure* ($C_{average\_6j} = C_{6_j} / N_{is}$)
2003	1	258,949
2004	11	37,109
2005	33	18,572
2006	22	34,555
2007	30	35,007
2008	45	26,747
2009	79	16,997
2010	49	31,527

The costs for providing on-site repair service in 2003 were excluded from the cost model as the cost data occurred under different service conditions (Chapter 7). Hence, the total travelling cost and the total number of on-site repair visits are established as:

Total travelling cost = 2,325,500 (9.7)

Total original number of on-site repair visits = 269 (9.8)

Based on values 9.7 and 9.8, the average travelling cost per on-site repair visit is calculated as:

The average travelling cost per on-site repair visit

= Total travelling cost / Original total number of on-site repair visits

= 2,325,500 /269

≈ RMB 8,645 (9.9)

Based on value 9.9, the eliminated travelling cost for 100 failures is calculated as:

Eliminated travelling cost

= The average travelling cost per on-site repair visit x new total number of on-site repair visits

= 8,645 x 100

≈ RMB 864,500 (9.10)

Step b) Moreover, as maintenance staff stay on-site, the original costs for phone service could also be eliminated, which is RMB 200,200 (Value 9.3).

Step c) The original costs of accommodation and meals could be neglected, as the maintenance staff would be responsible for finding accommodation and having meals, as they would be located at the customers' site as their place of work.

Based on Tables 7.11 and 7.13, the total original cost of accommodation and meals is established:

Total original cost of accommodation and means = 982,000 (9.11)

From values 9.8 and 9.11, the original average cost of accommodation and meals is calculated as:

The original average cost of accommodation and meals per on-site repair visit

= Total cost of accommodation and meals / Original total number of on-site repair visits

= 982,000 / 269

≈ RMB 3,651 (9.12)

Using value 9.12, the eliminated cost for accommodation and meals for 100 failures is calculated as:

The eliminated cost of accommodation and meals

= The original average cost of accommodation and meals per on-site repair visit x new total number of on-site repair visits

= 3,651 x 100

≈ RMB 365,100 (9.13)

Step d) Based on Tables 7.11 and 7.13, the total original cost of subsistence for travelling per on-site repair visit is established:

Total original cost of subsistence for travelling per on-site repair visit = 854,000 (9.14)

Applying values 9.8 and 9.14, the original average cost of subsistence for travelling per on-site repair visit is calculated as:

The original cost of subsistence for travelling per on-site repair visit
= Original total cost of subsistence for travelling / Original total number of on-site repair visits
= 854,000 / 269
≈ RMB 3,175 (9.15)

From value 9.15, the eliminated of subsistence for travelling per on-site repair visit for 100 failures is calculated as:

The eliminated costs of subsistence for travelling
= The average costs of subsistence for travelling per on-site repair visit x new total number of on-site repair visits
= 3,175 × 100
≈ RMB 317,500 (9.16)

Step e) The original costs of subsistence for travelling could be neglected, whereas the new costs of this variable were estimated for this scenario. It was assumed that approximately RMB 40,000 was considered as the costs of subsidies for travelling per maintenance staff. Hence, the total costs of subsidise for two maintenance staff was RMB 80,000.

Based on Steps a) to d), if sending two maintenance staff to the customer's company, the total costs could be saved is estimated as:

864,500 + 200,200 + 365,100 + 317,500 - 80,000 = RMB 1.7 millions

This is approximately 42% less than the total cost of providing engineering services support 100 machines when the maintenance staff are located at the XX Company. However, identifying where the cost benefit threshold occurs, i.e. when is it cost effective to base staff at the customers site is of interest to the engineering services providers.

Step 3) Propose how to allocate on-site repair staff based on the number of machines

Assuming the number of in-operation machines is x, a general relationship on how to allocate on-site repair staff based on the number of machines is generated by following steps 1 and 2. This relationship is established as:

The total losses or savings by allocating 2 staff (including 1 mechanical and 1 electrical) on-site for servicing x machines on a single site

$$= 17472.92x - 80000 \tag{9.17}$$

Based on Equation 9.17, how to allocate on-site staff based on the number of in-operation machines is presented in Table 9.6.

Table 9.6 Total losses or saving by allocating 2 staff on-site

The number of in-operation machines on a single site (x)	**The Total losses or savings by allocating 2 staff (1 mechanical and 1 electrical) on-site (17472.92x – 80000)**
1	-62,527
2	-45,054
3	-27,581
4	-10,108
5	7,365
10	94,729
20	269,458
30	444,188
40	618,917
50	793,646
60	968,375
70	1,143,104
80	1,317,834
90	1,492,563
100	1,667,292

From this table, the general trend is that as the number of machines on a single site increase, the more expenses that the XX Company would save by allocating two staff on-site. From the author's point of view, this general trend could be separated into four stages.

1) If there is less than 5 machines are on a single site, it is not advisable to allocate staff on-site, as the company requires extra costs for providing engineering services.

2) 5 machines are a turning point for the XX Company to start saving money by allocating two staff on-site. However, 2 to 20 machines are on a single site, a potential saving of approximately RMB 7,365 to 269,458 might not be enough cost motivation for the company to send staff on-site.
3) When the number of in-operation machines on a single site increase from 20 to 30, the potential saving for the company boosts from RMB 269,458 to RMB 444,188. 30-50 machines on a single site, it is suggested that the company could start considering the possibility of allocating two staff on-site to provide engineering services.
4) When the number of machines on a single site increases to 60 or more, it is strongly recommended that the company allocate staff on-site as this would help the company save around RMB 1 to 1.6 billion. For example, for a one-year engineering service contract for 100 machines, the XX Company would save approximately RMB 1,667,292 a year by allocating two staff on-site. By comparing this figure (RMB 1,667,292) to the original costs of providing on-site visits (RMB 2,864,500), this strategy could enable the original costs of providing on-site visits to be reduced by nearly 42%. Therefore, it seems appropriate to allocate two staff on-site for servicing 100 machines.

Apart from the cost factor, there are advantages and drawbacks of allocated staff on-site that the XX Company should consider. There are two major advantages of sending maintenance staff to work on-site. First, the technical problems related to the XX machine could be identified and fixed by two maintenance staff as quickly as possible. This not only saves time and effort for maintenance staff to travel, but also avoids misunderstanding over the phone when reporting a failure. Second, as the maintenance staff reside in the customer's company, they were more likely to gain a good interaction and bonding with the customers, especially with the machine operators. A better relationship would not only help XX maintenance staff to provide better engineering service but also perhaps win customers' loyalty, goodwill and potential business.

Nevertheless, the potential major downside of this strategy is that the customer might employ the maintenance staff. As the maintenance staff not only have valuable practical experience with the XX machines, but also the personality, capability and soft skills of maintenance staff might be observed and appreciated by the customers during their working on-site. Therefore, the XX Company might have to face the possibility of losing their dedicated maintenance staff. Consequently, the XX Company would need to recruit and train new staff for replacement, which might require a considerable amount of time, money and effort. To face this challenge, the possible solution for XX Company might be to swap the maintenance staff from one customer's company to other every year as well as send them to a site, which was not close to their hometown. The former would prevent the maintenance staff from developing a strong long-term relationship with the customer, whereas the latter could avoid the possibility that the staff might wish to settle down in the working city.

The XX Company could also sign a long-term contract with the maintenance staff before offering them an on-site job. Within the contract, an incentive or promotion deals could be included. For example, the bonus could be double or the maintenance staff could get promoted after a certain number of years being on-site. This might improve the loyalty of maintenance staff as well as help them plan their future in the long term.

9.4 Summary

To conclude, two scenarios were tested and analysed in this chapter. Based on the scenarios, the key outcomes were:

1) When 100 machines were provided on a single site, the costs for providing a one, three, five, seven, nine, eleven, thirteen and fifteen year service contract were estimated by the engineering services cost model using parametrics and the bathtub failure model.
2) When 5 machines were provided on a single site, XX customer could start saving expenses of approximately RMB 7,365 a year by sending two maintenance staff to customer's company.
3) When 60-100 machines were provided on a single site, XX customer could save expenses of approximately RMB 1-1.6 billion a year by sending two maintenance staff to customer's company.

In the next chapter, future work for this research is presented; in particular, recommendations for the engineering service cost model and possible service scenarios.

Chapter 10 Conclusions and Future Work

The overall aim of the research presented in this thesis was to estimate the cost of engineering services using parametrics and the bathtub failure model.

To achieve this overall aim four specific objectives were identified. Section 10.1, provides concluding comments on how the overall aim has been achieved and how each of the specific objectives contributed to the aim. Section 10.2 presents the finalised approach for estimating the cost of engineering services using parametrics and the bathtub failure model. Section 10.3 summarises the contribution to knowledge from this thesis. The contributions are classified in terms of the contribution made to academia, society and the industrial case study company. Section 10.4 then describes proposals for further research based on the findings and new knowledge gained from undertaking this PhD research programme.

10.1 Conclusions

The research presented in this thesis provides a step-by-step approach for estimating the cost of providing engineering services using parametrics and the bathtub failure model. The findings from the research undertaken show that this approach works and that parametrics can be used to estimate the cost of providing engineering services. This reflects the researcher’s view presented in Chapter 2, where based on her review of the literature and her analysis of product cost estimating techniques (Table 2.6). The parametric approach is appropriate when Cost Estimating Relationships can be identified. The findings from the research also demonstrated that as described in Chapter 3, that the bathtub failure model may also apply to systems rather than machine parts as independent entities. The historical data demonstrated that the machine failure rates followed the initial stages of the bathtub failure model and expert opinions suggested that the later stages of the bathtub failure model occurred after the machines had been in operation for nine years.

The conclusions reached, and how each of the specific objectives contributed to these conclusions are presented in the following section. The major outcomes of the thesis and how these link to the corresponding objectives and chapters are summarised below:

10.1.1 Objectives of Research

1) *Select an industrial case study, collect and analyse historical data from the case study company.*

   In the initial stages of the research questionnaires based on analysis and findings from the literature were sent to industrialists to ascertain their view on engineering service provision (Chapter 3). The findings from this survey identified how estimating the cost of providing engineering services was a challenge for industry. The applicability and use of the bathtub failure model was also introduced via discussions with industrial contacts.

   Based on the outcomes from the questionnaire, the nature of this research and personal contacts for collecting historical data, XX Company was selected as the industrial case study. Data was then collected and analysed from the case study company. A summary of documentary and questionnaire data with critique and analysis was presented (Chapter 6).

2) *Create an engineering service for the case study company.*

   By following step 2 of the proposed approach (Figure 5.1), the engineering services cost model was created. Performance attributes and CERs were defined. The cost model was then created based on these performance attributes and CERs. These provide the parametrics for use within the cost model (Chapter 7).

3) *Validate the engineering service cost model.*

   The cost model was validated by two groups of experienced experts from the XX Company. In particular, the model's process/logic, specifications, assumptions, performance factors and CERs were carefully scrutinised. The cost model was also validated by splitting the machine failure data into mechanical and electrical data. Finally, by utilising experts opinions, the cost model was validated and extended, which could be used to estimate the engineering services cost for up to 15 years. It is based on the historical data obtained from the XX Company and the views of the experts that the bathtub failure model is demonstrated to show that link between years in operation and failure rate occurrence. Here year nine is identified as the time when the machine starts to fail due to wear and tear (Chapter 8).

4) *Test service scenarios and propose service solutions with associated costing.* Further analysis of the engineering service cost model compared using '*what if*?' scenarios were undertaken. Two scenarios were presented and service solutions with associated costing were proposed. The findings from the scenario analysis illustrated how the different contract lengths and the failure attributes for the engineering service assets influence the pricing of the contract. It was also shown how to allocate on-site staff based on the number of in-operation machines from a single site. (Chapter 9)

10.2 Finalised Approach for Estimating the cost for engineering services

The finalised approach for estimating the cost for engineering services is presented in Figure 10.1. Step 3 of the approach, validate and extend the cost model by utilising experts opinions is added to the original approach shown in Figure 5.1. This is mainly because the historical data available (step 2) resulted in the initial stages of the bathtub failure model being shown. However, there was no historical data for the later years of engineering services. Hence, to ascertain expected failure rates where no data is available expert opinions were required. In this case the later stage of the bathtub failure model was predicted. Hence, the engineering services cost model is created based on parametrics as well as the bathtub failure model.

The additional activities are shown in step 3 of the step-by-step approach. Here based on the findings from this research it is recommended that if the historical data represents an exponential curve that expert opinions are elicited to ascertain whether the machines follow the bathtub failure model. In particular when the machines enter the wear-out behaviour phase is identified. This additional step is shown in bold in step three of Figure 10.1.

1. Select an industrial case study (Chapter 6)
- Reasons for selecting the case study company
- Research the background of the case study company
- Collect and analyse historical cost data from the case study company

⇩

2. Create an engineering services cost model (Chapter 7)
- Identify the scope and process of engineering services cost modelling
- Identify performance factors and CERs of the engineering services cost model
- Apply the bathtub failure model and stage within the bathtub using the historical data

⇩

3. Validate the engineering services cost model (Chapter 8)
- Validate the concept and principles of the engineering services cost model using experts opinions
- Validate the engineering services cost model by splitting the machine data into mechanical and electrical data
- **Validate and extend the cost model by utilising experts opinions**

⇩

4. Test service scenarios and propose service solutions with associated costing (Chapter 9)
- Propose how to price an engineering service contract based on 1, 3, 5, 7, 9, 11, 13 and 15 years in operation
- Propose how to allocate on-site staff based on the number of machines in operation

Figure 10.1 Finalised approach for estimating the cost for engineering services using parametrics and the bathtub failure model

10.3 Contribution to Knowledge

<u>The dominant contribution of this research:</u>

Creation of an approach to estimate the cost of engineering services using parametrics and the bathtub failure model.

<u>Contributions to the XX Company</u>:

As the proposed approach and the engineering services cost model were developed based on the XX Company, the outcome of this research helped the Company in a number of different aspects.

- The proposed approach provides a systematic and step-by-step approach for cost estimators to estimate the costs of providing engineering services.

- The engineering services cost model assists the XX Company to understand the costs for providing engineering service contracts of different lengths.

- The scenarios described in Chapter 9 enables XX managers/decision makers to decide on providing engineering service contracts of different lengths and to make arrangements with regards to their maintenance staff, in particular to determine when it is more cost effective to provide dedicated maintenance staff to be based at their customer sites.

<u>*Contributions to society*</u>:

Cost estimators:

- The proposed approach provides a starting point in terms of the directions and guidance for cost estimators to estimate the cost of engineering services in different domains, such as aerospace, defense, construction and manufacturing sectors. Consequently, the estimated engineering services value would help the service provider to plan for the future, win engineering service contracts, and gain on-going profits.

Service Suppliers:

- The proposed service solutions presented in Chapter 9 provide general guidance for service suppliers to consider the possible aspects of providing a long-term engineering service contract. Thus, the engineering services cost model could act as a useful tool for suppliers during the bidding and in-operation stages for engineering services.

Customers:

- The proposed approach helped the customers to understand how their engineering services were estimated and charged. Hence, this would help them to negotiate with their service suppliers for engineering service contract.

10.4 Future Work

The proposed approach and the engineering services cost model using parametrics and the bathtub failure model could be further improved when the following future work proposals are carried out.

10.4.1 Multiple Case Studies

There are several ways to improve the current research the first being the use of multiple case studies to ascertain the approaches availability across other sectors.

1) Although the performance factors and CERs were mainly developed based on a single case study company, the approach of estimating the cost for providing engineering services might be likely to apply to other cases. Currently, the proposed approach was tested and validated within the XX Company. However, if multiple case studies are available, the framework for estimating the cost of providing engineering services to XX Company could be applied to other case study companies. Hence, the approach could be validated in different industrial sectors.

2) If various case studies from different industrial sectors are available, a diverse range of data could be collected and analysed. Based on this data, common key cost-related attributes might be discovered for different applications. For example, Company A is an engine service provider, Company B is a machine service provider and Company C is a submarine service provider. Although they are providing engineering services to different products, the cost-related attributes, such as corrective maintenance, preventative maintenance, maintenance staff, might all have a profound impact on the costs of providing engineering services. Hence, each of the attributes could establish CERs to enrich and broaden the scope of the engineering services cost model, which makes the model more realistic and useable for different case studies.

3) Another suggestion is that estimating the cost of providing engineering training services could enhance the engineering services cost model. A good training program provided to machine operators will assist in the proper operation of the

machine, reducing the number of failures and consequently reducing engineering services costs. Hence, it might be useful to conduct research in this area in order to provide better engineering services.

10.4.2 Intangible attributes of the Engineering Services Cost Model

The proposed approach was able to estimate the costs of tangible engineering services provisions, however the intangible attributes of providing such services could be an important direction for further research. In the researcher's opinion, there are several key attributes should be considered for estimating the costs of intangible engineering services.

First, the relationship between the customers and the service providers might influence the cost of providing engineering services. With a better relationship between these two entities, customers might provide feedback on how to improve the engineering services and hence help the company to offer better engineering services at lower costs. Customers were also likely to purchase additional machines and entered into longer engineering service contracts, which help the service supplier to obtain on-going profit and reduce the unit cost for providing the engineering services. Moreover, if customers are satisfied with the engineering services offered by the service provider, they might recommend it other companies. Hence, this would not only help them to expand their market, but also gain profit in a long term.

A closer and bonded relationship between the customers and the service providers can also benefit the customers. It is suggested that when the existing customer purchased addition machines or entered a longer engineering service contract, a better service deal or a discount might be obtained. For example, the longer the engineering service contract that the customer entered, the better the discount offered. To achieve this the cost of providing engineering service contracts at different years should be estimated. Moreover, a better relationship might also encourage the service provider to give better engineering services to the customers. For example, they may delegate the most experienced and knowledgeable maintenance staff to work on-site or consider the problems related to their machines as a priority.

Because it seems that a better relationship could result in a win-win situation between the customers and the service provider, it would be useful to consider this attribute in the engineering services cost model. A rating scale could be designed between the customer-service supplier and the cost for providing engineering services. A higher scale factor may suggest lower potential costs for providing such services.

Second, the relationship between the machine operators from the customer's site and the maintenance staff from the service provider are considered to have an impact on the cost of providing engineering services. For example, maintenance staff had a better relationship with operator A than operator B. When machines A and B failed simultaneously, maintenance staff might offer engineering services to machine A as priority because he had a closer link with operator A. Moreover, during the on-site repair services to machines A and B, the maintenance staff perhaps tended to provide better engineering services to operator A. For instance, giving a gentle reminder on how to maintain and repair the machine, or a lesson on easier ways to identify a mechanical problem.

To ensure the standard and quality of providing engineering services to different customers are consistent, it would be useful to set a benchmark for maintenance staff to provide such services. For example, the benchmark could include routine activities, such as a brief welcome, enquiry on how the operator used the machine and how the machine performed abnormally for each on-site repair services. Meanwhile, the maintenance staff should be provided with routine training on human skills, such as how to communicate and co-operator with machine operators effectively and how to deliver the engineering services in an appropriate manner. Nevertheless, there might be a relationship between the maintenance staff-operator and the costs of delivering engineering services. Consequently, the CER related to this attribute should be considered in the engineering services cost model.

As a whole, if multiple case studies or more historical data were available, both the proposed approach and the engineering services cost model could be further developed and improved. In parallel with this, the intangible characteristics of the engineering services could be considered and further researched. Hence, the proposed approach and engineering services cost model would be more practical and commercial.

References

1. **Aamodt, A.** and **Plaza, E.** (1994). Case based reasoning: foundational issues, methodological variations, and system approaches. *Artificial Intelligence Communications.* **7**(1): 39-59.

2. **Aarset, M. V.** (1987). How to identify a bathtub hazard rate. IEEE Transactions on Reliability. **36**(1): 106-108.

3. **ABB**. (2011). Available online at: http://www.abb.co.uk/ServiceGuide/Default.aspx (Assessed April 2011).

4. **ACEIT.** (2012). Available online at: http://www.aceit.com/ (Assessed January 2012).

5. **Ahsanullah, M. and Hamedani, G. G.** (2010). *Exponential distribution: theory and methods.* New York: Nova Science Publishers Inc.

6. **Andrews, J. D.** and **Moss, T. R.** (1993). Reliability and risk assessment, Harlow: Longman.

7. **Asiedu, Y.** and **Gu, P.** (1998). Product life cycle cost analysis: state of the art review. *International Journal of Production Research*, **36**(4): 883-908.

8. **Attarzadeh, I.** and **Ow, S. H.** (2011). Improving estimation accuracy of the COCOMOII using an adaptive fuzzy logic model. *2011 IEEE International Conference on Fuzzy Systems*, June 27-30, Taipei, Taiwan, 2458-2464.

9. **AVICO.** (2009). Available on line at: http://www.avicoair.com/ (Assessed March 2009).

10. **Azzeh, M., Neagu, D.** and **Cowling P. I.** (2010). Fuzzy grey relational analysis for software effort estimation. *Empirical Software Engineering,* 15(1): 60-90.

11. **BAE Systems**. (2011). Available on line at: http://www.baesystems.com/what-we-do-rzz/products--services/military--technical-services?_afrLoop=476956580984000 (Assessed March 2011).

12. **BAE Systems**. (2012). Available on line at: http://www.baesystems.com/our-company-rzz/our-businesses/maritime-services/about-us?_afrLoop=450331505169000 (Assessed May 2012).

13. **Banga, K.** (2010). A comparison of case-based reasoning and regression analysis approaches for cost uncertainty modelling. Maters Thesis, Missouri University of Science and Technology, Department of Mechanical Engineering.

14. **Baines, T. S., Lightfoot, H. W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J. R., Angus, J. P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I. M.** and **Wilson, H.** (2007). State-of-the-art in product-service-system. *Proceedings of the Institution of Mechanical Engineerings. Part B, Journal of Engineering Manufacturing*. 221(10), pp.1543-1552.

15. **Baines, T.** (2011). Servitization within manufacturing: exploring the provision of advanced services and their impact on vertical integration. *Journal of Manufacturing Technology Management.* **22**(7): 947-954.

16. **Ben-Arieh, D.** and **Qian, L.** (2003). Activity-based cost management for design and development stage. *Int. J. Production Economics*. **83**: 169-183.

17. **Blessing, L.T.M. and Chakrabarti, A.** (2009). DRM, a Design Research Methodology, London: Springer

18. **Blocher, E.J., Chen, K. H., Cokins, G.** and **Lin, T. W.** (2005). *Cost management: a strategic emphasis*, 3rd ed. Boston, Mass.; London: McGraw-Hill/Irwin.

19. **Brannen, J.** (2005). Mixing methods: the entry of qualitative and quantitative approaches into the research process. *International Journal of Social Research Methodology,* **8**(3): 173-184.

20. **Bode, J.** (1998). Neural networks for cost estimation. *American Association of Cost Engineers*. **40**(1): 25-30.

21. **Bowman. R. A.** and **Schmee, J.** (2001). Pricing and managing a maintenance contract for a fleet of aircraft engines. *Simulation.* 76(2): 69-77.

22. **Brax, S.** (2005). A manufacturer becoming service provider – challenges and a paradox. *Managing Service Quality*, 15(2), pp. 142-155.

23. **Briand, L. C., Emam, K. E., Surmann D., Wieczorek, I.** and **Maxwell, K. D.** (1999). An assessment and comparison of common software cost estimation modelling techniques. *Proceedings of the 1999 International Conference on Software Engineering.* pp. 313-323.

24. **Bryman, A.** (2008). *Social research methods.* 3rd ed. Oxford: Oxford University Press.

25. **Camargo, M., Rabenasolo, B., Jolly-Desodt, A-M.** and **Castelain, J-M.** (2003). Application of the parametric cost estimation in the textile supply chain. *Journal of Textile and Apparel, Technology and Management.* 3(1):1-12.

26. **Carer, P., Aupied, J, Malarange, G., Gougeon, S.** and **Spelleman, C.** (2004). Experience feedback and maintenance policies of substations and

electrical equipment in EDF’s distribution MV and LV networks, and RTE’s VHV and HV networks. *8th International Conference on Probabilistic Methods Applied to Power Systems*. pp.313-318.

27. **Castagne, S., Curran, R., Rothwell, A., Price, M., Benard, E.,** and **Raghunathan, S.** (2008) A generic tool for cost estimating in aircraft design. *Research in engineering design*, **18**(4): 149-162.

28. **Catania, G.** (1991). Form-features for mechanical design and manufacturing. *Journal of engineering Design*. **2**(1): 21-43.

29. **Cavalieri, S., Maccarone, P.** and **Pinto, R.** (2004). Parametric vs. neural network models for the estimation of production costs: a case study in the automotive industry. International Journal of Production Economics. 91: 165-177.

30. **CET, Cost Engineering Terminology.** (2010). AACE International Recommended Practice No. 10S-90, Available on line at: http://www.aacei.org/technical/rps/10s-90.pdf [Accessed 6th October 2010].

31. **Chan, D. S. K.** (2003). Expert system for product manufacturability and cost evaluation. *Materials and Manufacturing Processes,* **18**(2): 313-322.

32. **Cheung, W. M., Newnes, L. B., Mileham, A. R., Marsh, R.** and **Lanham, L. D.** (2007a). A study of life cycle costing in the perspectives of research and commercial applications in the 21st century. *Proceedings of ASME 2007 International Design Engineering and Technical Conferences and Computers and Information in Engineering Conference,* September 4-7, Las Vegas, Nevada, USA.

33. **Cheung, W. M., Newnes, L. B., Mileham, A. R., Marsh, R.** and **Lanham, L. D.** (2007b). Cost estimation in product development: academic research and commercial systems evaluation. *Proceedings of the 4th International Conference on Digital Enterprise Technology,* September 19-21, Bath, UK.

34. **Cheung, W. M., Marsh, R., Newnes, L. B., Mileham, A. R.** and **Lanham, J. D.** (2009a). Standards and inference of design information in through-life costing of innovative defense electronic products. *Proc. IMechE Part B: J. Engineering Manufacture*, 223, pp. 169-181.

35. **Cheung, J. M. W., Scanlan, J. P.** and **Wiseall, S. S.** (2009b). An aerospace component cost modelling study for value driven design. In: CIRP IPS2 Conference: Industrial Product-Service Systems, Cranfield, UK, 01-02 April 2009. 5pp.

36. **Chou, J. S.** and **Tai, Y.** (2010). Generalized regression neural nets in estimating the high-tech equipment project cost. *2010 Second*

International Conference on Computer Engineering and Applications, 2:281-284.

37. **Clark, F. D.** (1985). *Applied Cost Engineering*. 2nd ed., New York, Basel:Dekker.

38. **CMMI for Services.** (2009). Version 1.2. Available online at: http://www.sei.cmu.edu/reports/09tr001.pdf [Accessed 6th October 2009].

39. **Creswell, J. W.** (2007). *Qualitative inquiry and research design: Choosing among five approaches*, 3rd ed. Thousand Oaks, CA: Sage.

40. **Creswell, J. W.** (2009). *Research design: Qualitative, quantitative, and mixed methods approaches*, 3rd ed. Thousand Oaks, CA: Sage.

41. **Cook, M. B., Bhamra, T. A.** and **Lemon, M.** (2006). The transfer and application of product service systems: from academia to UK manufacturing firms. *Journal of Cleaner Production*, 14(17): 1455-1465.

42. **Das, K.** (2008). A comparative study of exponential distribution vs weibull distribution in machine reliability analysis in a CMS design. *Computer & Industrial Engineering,* 54: 12-33.

43. **Datta, P. P.** and **Roy, R.** (2010). Cost modeling techniques for availability type service support contracts: A literature review and empirical study. *CIRP Journal of Manufacturing Science and Technology*, 3(2), pp.142-157.

44. **Davies, A.** (2003). Are firms moving 'downstream' into high-value services? in Tidd, J. and Hull, F.M. (Eds), Service Innovation, Series on Technology Management, Vol. 9, Imperial College Press, London, pp. 21-34.

45. **Davies, A., Brady, T.** and **Hobday, M.** (2006). Charting a path toward integrated solutions. *MIT Sloan Management Review,* **47**(3): 39-48.

46. **DeccaPro.** (2009). Available on line at: www.deccansystems.com/ [Accessed October 2009].

47. **Deng, J.L**. (1982). Control problems of grey system. *Systems Control Lett.* **5**: 285-294.

48. **Deng, J.L.** (1989). Introduction to grey system theory. *J Grey Systems.* **1**: 1-24.

49. **Denscombe, M.** (1998). *The Good Research Guide for small-scale social research projects.* Scarborough, Great Britain: Biddles Ltd.

50. **DFMA.** (2009). Available on line at: www.dfma.com/ [Accessed September 2009].

51. **Dhillon, B. S.** (2010). *Life Cycle Costing for Engineers*. London: Taylor and Francis Group.

52. **Diallo, M. Pierreval, H.** and **Quilliot, A.** (2001). Manufacturing cells design with flexible routing capability in presence of unreliable machines. *International Journal of Production Economics*, 74: 175-182.

53. **Duverlie, P.** and **Castelain, J.M.** (1999). Cost estimation during design step: parametric method versus case based reasoning method. *Int J Adv Manuf Technol*. (15): 895-906.

54. **Feng, C.X., Kusiak, A.** and **Huang, C. C.** (1996). Cost evaluation in design with form features. *Computer-aided design*. **28**(11): 879-885.

55. **Flyvbjerg, B.** (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*. 12(2): 219-245.

56. **Galbraith, J. R.** (2002). Organizing to deliver solutions. *Organizational Dynamics*. **31**(2): 194-207.

57. **Glasow, P. A. (2005).** Fundamentals of survey research methodology. *MITRE Washington C3 Center*, Virginia.

58. **Gayretli, A.** and **Abdalla, H. S.** (1999). An object-oriented constraints-based system for concrrent product development. *Rob. Comput.-Integr. Manufactu.* **15**: 133-144.

59. **Goh, Y. M., Newnes, L. B., Mileham, A. R., McMahon, C. A.** and **Saravi, M. E.** (2010). Uncertainty in Through-Life Costing – Review and Perspectives. *IEEE Transactions on Engineering Management*. **57**(4): 689-701.

60. **Gray, B.** (2009). Review of acquisition for the secretary of state for defence. Available online at: http://www.mod.uk/NR/rdonlyres/78821960-14A0-429E-A90A-FA2A8C292C84/0/ReviewAcquisitionGray_report.pdf (assessed April 2010).

61. **Guba, E.G.** and **Lincoln, Y.S.** (1994). Competing paradigms in qualitative research. In N.K. Denzin and Y. S. Lincoln (Eds.) *Handbook of Qualitative Research*. Thousand Oaks, CA: Sage.

62. **Gummesson, E.** (1991). *Qualitative Methods in Management Research.* Newbury Park, California, United States of America: Sage Publications, Inc.

63. **Guy Salmon.** (2012). Available online at: http://www.sytner.co.uk/guy-salmon-land-rover/home.aspx (Assessed April 2012).

64. **Hain, S. and Back, A.** (2011). Towards a maturity model for E-collaboration – a design science research approach. *Proceedings of the 44th Hawaii International Conference on System Sciences.* pp: 1-10.

65. **Herrman, C. S.** (2009). Fundamentals of methodology Part I definitions and first principles. Available online at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1373976 (assessed April 2011).

66. **Huang, J.** (1996). A quantitative method used in negotiation support systems. *Computers and Industrial Engineering*. **31(**3/4): 821-826.

67. **Huang, X., Ho, D., Ren, J.** and **Capretz, L. F.** (2006). A soft computing framework for software effort estimation. Soft Computing, A Fusion of Foundations Methodologies and Applications Journal, **10**(2): 170-177.

68. **Huang, X. X., Newnes, L. B.** and **Parry, G. C.** (2009). A critique of product and service based systems. In: Ceglarek, D., ed. *Advances in Manufacturing Technology - XXIII: Proceedings of the 7th International Conference on Manufacturing Research (ICMR2009)*, Nottingham: Salient Books. pp.: 405-412.

69. **Huang, X.X., Newnes, L.B.** and **Parry, G.C.** (2011). An analysis of industrial practice for estimating the in-service costs of a product service system. *Proceedings of the ASME 2011 International Design Engineering Technical Conference & Computers and information in engineering Conference*. August 28-31, 2011, Washington, DC, USA.

70. **Huang, X. X., Newnes, L. B.** and **Parry, G. C.** (2012). The adaptation of product cost estimation techniques to estimate the cost of service. *International Journal of Computer Integrated Manufacturing*, **25**(4-5): 417-431.

71. **Hundal, M. S.** (1993). *Design to cost*. Concurrent Engineering: contemporary issues and modem design tools, H.R. Parsaei and W. G. Sullivan, eds., Chapman and Hall, London pp.: 330-351.

72. **ICCWare. (2012).** Available on line at: www.isograph-software.com/ [Accessed January 2012].

73. **Jager, P.** and **Bertsche, B.** (2004). A new approach to gathering failure behavior information about mechanical components based on expert knowledge. 2004 Annual Symposium (RAMS) - Reliability and Maintainability. pp: 90-95.

74. **Jia, J., Jia, X.** and **Tian, C.** (2009). The application of BP neural net model in logistics costs decision-making. *International Conference on Computational Intelligence and Software Engineering, CiSE,* pp: 1-4.

75. **Jia, Z., Liu, W., Hou, Z.** and **Lv, W.** (2009). Research on operation cost of helicopter components based on flight condition. *International Conference on Reliability, Maintainability and Safety, ICRMS,* pp: 274-277.

76. **Jian, L.** and **Hong-fu, Z.** (2004). The predictive models of maintenance costs for a civil airplane. *Proc. Instn Mech, Engrs Part G: J. Aerospace Engineering.* 218: 347-351.

77. **Jiang, G., Wang, Y.** and **Liu, H.** (2010). Research on software cost evaluation model based on case-based reasoning. *2010 Second WRI World Congress on Software Engineering.* 2: 338-341.

78. **Jung, J.Y.** (2002). Manufacturing cost estimation for machined parts based on manufacturing features. *J. Intell. Manuf.* **13**(4): 277-238.

79. **Kahn, B. K., Strong, D. M.** and **Wang, R. Y.** (2002). Information quality benchmarks: product and service performance. Communications of the ACM, **45**(4):184-192.

80. **KAPES.** (2012). Available on line at: www.kapes.com/ (Accessed January 2012).

81. **Khataie, A. H., Bulgak, A. A.** and **Segovia, J. J.** (2010). Advanced decision support tool by integrating activity-based costing and management to system dynamics. *Technology Management for Global Economic Growth (PICMET), 2010 Proceedings of PICMET'10,* pp.:2387-2390.

82. **Khatod, D. K., Pant, V.** and **Sharma, J.** (2010). Analytical approach for well-being assessment of small autonomous power systems with solar and wind energy sources. *IEEE Transactions on Energy Conversion,* 25(2): 535-545.

83. **Kleijnen, J. P. C.** (1995). Verification and validation of simulation models. *European Journal of Operational Research.* **82**(1): 145-162.

84. **Klutke, G. A., Kiessler, P. C**. and **Wortman, M. A.** (2003). A critical look at the bathtub curve. *IEEE Transactions on Reliability*. **52**(1): 125-129.

85. **Kuhnert, P. M., Hayes, K., Martin, T. G.** and **McBride, M. F.** (2009). Expert opinion in statistical models, *18th World IMACS/MODSIM Congress,* Cairns, Australia, 13-17 July.

86. **Kumar, R.** (2005) *Research methodology*, 2nd ed. London: Sage Publications.

87. **Kumar, S., Krishna, B. A.** and **Satsangi, P. S.** (1994). Fuzzy systems and neural networks in software engineering project management. *Journal of Applied Intelligence*, **4**(1): 31-52.

88. **Kung, H. J.** (2004). Quantitative method to determine software maintenance life cycle. *Proceedings of the 20th IEEE International Conference on Software Maintenance (ICSM'04),* pp: 232-241.

89. **Lanza, G.** and **Ruhl, J.** (2009). Simulation of service costs throughout the life cycle of production facilities. *CIRP Journal of Manufacturing Science and Technology*, 1: 247-253.

90. **LCCWare.** (2012). Available on line at: www.isograph-software.com/ (Accessed January 2012).

91. **Lee, T., Baik, D.** and **In H. P.** (2008). Cost benefit analysis of personal software process training program

92. **Lewis, J.** (2000). Metrics mapping cuts estimating time. *Des. News.* **55**(18): 107-110.

93. **Lin, Z.C.** and **Chang, D.Y.** (2002). Cost-tolerance analysis model based on a neural networks methods. *International Journal of Production Research*. **40**(6): 1429-1452.

94. **Maillart, L. M.** and **Pollock, S. M.** (1999). The effect of failure-distribution specification-errors on maintenance costs. *1999 Proceedings Annual Reliability and Maintainability Symposium,* pp.69-77.

95. **Mak, S. T.** (1987). Random failure statistics and replacement schedules of remote devices for load management. *IEEE Transactions on Power Systems*. **2**(2): 451-457.

96. **Mathaisel, D. F. X., Manary, J. M.** and **Comm, C. L.** (2009). Military Enterprise Sustainability: Enhancing the military's ability to perform the mission, CRC Press, United States of America: Taylor & Francis Group.

97. **Melbourne Autos.** (2012). Available on line at: http://www.melbourne-autos.co.uk/ (Accessed May 2012).

98. **Meier, H., Roy, R.** and **Seliger, G.** (2010). Industrial product-service systems-IPS^2. *CIRP Annals – Manufacturing Technology*. 59: 607-627.

99. **Mileham, A. R., Currie, G. C., Miles, A. W.** and **Bradford, D. T.** (1993). A parametric approach to cost estimating at the conceptual stage of design. *Journal of Engineering Design*. **4**(2): 117-125.

100. **Mittas, N., Athanasiades, M.** and **Angelis, L.** (2008). Improving analogy-based software cost estimation by a resampling method. *Information and Software Technology.* 50: 221-230.

101. **Moss, M. A.** (1985). *Designing for minimal maintenance expense: the practical application of reliability and maintainability*. New York: Dekker.

102. **Murphy, M. D.** (2012). Reliability centered prediction technique for diagnostic modelling and improvement. Available on online at: http://web.engr.oregonstate.edu/~paasch/murphy.pdf [Accessed March 2012].

103. **Nan, L.** (2010). Based on dynamic regression model medium and long-term demand forecast and analysis of China's electric power. *International Conference on Information Science and Engineering (ICISE)*. pp: 1053-1056.

104. **NASA.** (2012). Cost Estimating Guideline. Available on online at: http:// cost.jsc.nasa.gov/guidelines.html [Accessed January 2012].

105. **Neely, A.** (2007). The servitization of manufacturing: an analysis of global trends. *Proceedings of the 14th European Operations Management Association Conference*, Bilkent University/Tubitak, Ankara, Turkey.

106. **Neely, A.** (2008). Exploring the Financial Consequences of the Servitization of Manufacturing. *Operations Management Research*, 1(2): pp. 103-118.

107. **Newnes, L. B., Mileham, A.R.** and **Hosseini-Nisab, H.** (2007). On-screen real-time cost estimating. *International journal of production research*, **45**(7), pp.1577-1594.

108. **Newnes, L. B., Mileham, A.R., Cheung, W. Lanham, J. D., Saravi, M. E.** and **Bradbery, R. W.** (2008). Predicting the whole-life cost of a product at the conceptual design stage. *Journal of Engineering Design*. **19**(2): 99-112.

109. **Niazi, A., Dai, J. S., Balabani, S.** and **Seneviratne, L.** (2006). Product cost estimation: Technique classification and methodology review," Journal of Manufacturing Science and Engineering**, 128**(2), pp. 563-575.

110. **Niglas, K.** (2004). The combined use of qualitative and quantitative methods in educational research. PhD Thesis, Tallinn Pedagogical University, Department of Educational Sciences.

111. **NIST/SEMATECH**, e-Handbook of Statistical Methods. (2012). Available on line at: http://www.itl.nist.gov/div898/handbook/ (Accessed March 2012).

112. **O'Connor, P. D. T.** (1991). *Practical reliability engineering*. 3rd ed. Wiley.

113. **Omar, M. F., Trigunarsyah, B. and Wong, J.** (2009). A design science approach for consultant selection decision support system. 4th *International Conference on Cooperation and Promotion of Information Resources in Science and Technology,* pp: 90-94.

114. **Ostwald, P. F.** (1991). *Engineering Cost Estimating*, 3rd ed., Prentice Hall, Englewood Cliffs, NJ.

115. **Ou-Yang, C.** and **Lin, T. S.** (1997). Developing an integrated framework for feature-based early manufacturing cost estimation. *International Journal of Advanced Manufacturing Technology.* 13: 618-629.

116. **Oxford English Dictionary**. (2009). Available online at: http://dictionary.oed.com/cgi/entry/00307811?single=1&query_type=word&queryword=methodology&first=1&max_to_show=10 (Accessed September 2009).

117. **Parametric Cost Estimating Handbook**. (2012). Available online at: http://cost.jsc.nasa.gov/PCEHHTML/pceh.htm (Accessed March 2012).

118. **Park, S., Hartley, J.L.,** and **Wilson, D.** (2001). Quality management practices and their relationship to buyer's supplier ratings: a study in the Korean automotive industry. *Journal of Operations Management*, **19**: 695-712.

119. **Park, J. H., Seo, K.K., Wallace, D.,** and **Lee, K. I.** (2002). Approximate product life cycle costing method for the conceptual product design. *CIRP Annals - Manufacturing Technology*. **51**(1): 421-424.

120. **Patel, N.A.** (2011). Decision Making at the Contract Bidding Stage. Masters Thesis, University of Bath, Department of Mechanical Engineering.

121. **Pereira, M. V. F., Maceira, M. E. P., Oliveira, G. C.** and **Pinto, L. M. V. G.** (1992). Combining analytical models and monte-carlo techniques in probabilistic power system analysis. Transactions on Power Systems, **7**(1): 265-272.

122. **Pipino, L. L., Lee, Y. W.** and **Wang, R. Y.** (2002). Data quality assessment. Communications of the ACM, **45**(4): 211-218.

123. **Pulsar.** (2009). Shore Software, Inc., Available online at: http://www.estimatingsystems.com/ (Accessed August 2009).

124. **Qi, Y., Lu, Z.** and **Song, B. (2003).** New concept for aircraft maintenance management (II) – The establishment of the spoon-shaped curve model. *Proceedings of the Annual Reliability and Maintainability Symposium.* pp: 68-73.

125. **Rajasekar, S., Philominathan, P.** and **Chinnathambi, V.** (2006). Research methodology. Available online at: http://arxiv.org/abs/physics/0601009/ (Assessed October 2010).

126. **Relex LCC. (2009).** Available online at: www.relexsoftware.co.uk/ (Assessed October 2009).

127. **PRICE Modules,** PRICE Systems. (2011). Available online at: http://www.pricesystems.com (assessed August 2011).

128. **Roy, R., Kelvesjo, S., Forsberg, S.,** and **Rush, C.** (2001). Quantitative and qualitative cost estimating for engineering design. *Journal of Engineering Design.* **12**(2): 147-162.

129. **Roy, R.,** and **Kerr, K.** (2003). Cost Engineering: why, what and how? *Decision Engineering Report*, Series ISBN 1-861940-96-3.

130. **Rolls-Royce.** (2009). Available online at: http://www.rolls-royce.com/reports/2009/overview/our-business.shtml (assessed April 2009).

131. **Rolls-Royce.** (2010). Available online at: http://www.rolls-royce.com/civil/news/2010/101122_china_easter_order.jsp (assessed November 2010).

132. **Rolls-Royce.** (2011). Available online at: http://www.rolls-royce.com/services/ (assessed May 2011).

133. **Sarantakos, S.** (2005). *Social Research*, 3rd ed. New York: Palgrave Macmillan.

134. **Sargent, R. G.** (2005). Verification and validation of simulation models. *Proceedings of the 2005 Winter Simulation Conference.* pp:130-143.

135. **Scanlan, J., Rao, A., Bru, C., Hale, P.** and **Marsh, R.** (2006). DATUM project: Cost estimating environment for support of aerospace design decision making. *Journal of aircraft*, 43(4), pp, 1022-1028.

136. **SEER-H** and **SEER-DFM,** Galorath Incorporated. (2009). Available online at: http:// www.galorath.com (assessed August 2009).

137. **Shehab, E.M.** and **Abdalla, H.S.** (2001). Manufacturing cost modelling for concurrent product development. *Robotics and Computer Integrated Manufacturing*. **17**(4):341-353.

138. **Shehab, E.M.** and **Abdalla, H.S.** (2002). A design to cost system for innovative product development. *Proceedings of the Institution of Mechanical Engineering. Part B, Journal of engineering manufacture*, **216**(7): 999-1019.

139. **Shostack, G. L.** (1984). Designing services that deliver. *Harvard Business Review.* **62**(1): 133-139.

140. **Shostack, G. L.** (1987). Service positioning through structural change. *Journal of Marketing.* **4**(2): 73-80.

141. **Silva, C. M. I. D., Cabrita, C. M. P.** and **Matias, J. C. D. O.** (2008). Proactive reliability maintenance: a case study concerning maintenance service costs. *Journal of Quality in Maintenance Engineering*, **14**(4): 343-355.

142. **Smith, A.E.** and **Mason, A.K.** (1997). Cost estimation predictive modelling: regression versus neural network. *Engineering Economist,* **42**(2): 137-162.

143. **Sohn, S. Y., Kim, Y.** and **Kim, B. T.** (2009). Cost of ownership model for spare engines purchase for the Korean navy acquisition program. *Journal of the Operational Research Society,* 60: 1674-1682.

144. **Son, J.** (1991). A cost estimation model for advanced manufacturing systems. *International Journal of Production Research,* **29**(3): 441-452.

145. **Song, H., Lee, S. I.** and **Youn, C. H.** (2005). Operation cost model based configuration management policy in OBS networks. *TENCON 2005 IEEE Region 10*, pp: 1-5.

146. **Spinato, F., Tavner, P. J., Van Bussel, G. J. W.** and **Koutoulakos, E.** (2009). Reliability of wind turbine subassemblies. *IET Renewable Power Generation*, **3**(4): 387-401.

147. **Stake, R. E.** (1995). *The art of case study research*. Thousand Oaks, CA: Sage.

148. **Tan, S. S., Rutten, F. F. H., Van Ineveld, B. M., Redekop, W. K.** and **Roijen, H.** (2009). Comparing methodologies for the cost estimation of hospital services. *European Journal of Health Economics.* **10**(1): 39-45.

149. **Thompson, P.** (2004). Researching family and social mobility with two eyes: some experiences of the interaction between qualitative and quantitative data. *International Journal Social Research Methodology*, **7**(3): 237-257.

150. **Turnbull, S.** (2002). Social construction research and theory building. *Advances in Developing Human Resources*. **4**(3): 317-334.

151. **Valerdi, R., Ross, A. M.** and **Rhodes, D. H.** (2007). A framework for evolving system of systems engineering. *Cross Talk*. **20**(10): 28-30.

152. **Villarreal, J. A., Lea, R. N.** and **Savely, R. T.** (1992). Fuzzy logic and neural network technologies. *In: 30th Aerospace Sciences Meeting and Exhibit*, Houston, Texas, January 6-9.

153. **Wallace, J. M., Houser, S. A.** and **Lee, D. A.** (2000). A physics-based alternative to cost-per-flying-hour models of aircraft consumption costs. Technical Report. Available online at: http://data.un.org/Glossary.aspx?q=goods (Accessed October 2008).

154. **Ward, Y.** and **Graves, A.** (2007). Through-life management: the provision of total customer solutions in the aerospace industry. *Int. J. Services Technology and Management,* **8**(6), pp. 455-477.

155. **Wilkins, D. J.** (2012). The bathtub curve and product failure behaviour. Available online at: http://www.weibull.com/hotwire/issue21/hottopics21.htm and http://www.weibull.com/hotwire/issue22/hottopics22.htm (Access March, 2012).

156. **Williams, R**. **G.** (1992). An intuitive parametric cost forecasting model for assembled products. *Technology Management: the New International Language*, 304-308.

157. **Wolfenstetter, S. B.** (2011). Conceptual framework for standard economic evaluation of physical activity programs in primary prevention. *Prevention Science*, 12:435-451.

158. **Xia, E., Jurisica, I., Waterhouse, J.** and **Sloan, V.** (2010). Runtime estimation using the case-based reasoning approach for scheduling in a grid environment. *ICCBR'10 Proceedings of the 18th international conference eon case-based reasoning research and development*, 6176: 525-539.

159. **Xu, X., Chen, J. L. Q.** and **Xie, S. Q.** (2006). Framework of a product lifecycle costing system. *Journal of Computing and Information Science in Engineering,* 6, pp: 69-77.

160. **Yang, L. Xing, K.** and **Lee, S. H.** (2010). A new conceptual life cycle model for result-oriented product – service system development. *2010 IEEE International Conference on Service Operations and Logistics and Informatics.* pp: 23-28.

161. **Yin, R. K.** (2003). *Case study research: design and methods.* 3rd ed. Thousand Oaks, California, United States of America: Sage Publications, Inc.

162. **Zhang, Y. F., Fuh, J. Y. H.** and **Chan, W. T.** (1996). Feature-based cost estimation for packaging products using neural networks. *Computers in Industry.* **32**: 95-113.

163. **Zhong, Y.** and **Liu, H.** (2010). A research methodology for green IT systems based on WSR and design science: the case of a Chinese company. *Communications in Computer and Information Science.* 113: 215-225.

Appendix A Questionnaire about Cost Estimation with Cost Estimators

(Survey Target: experienced cost estimators)

Company Name: ____________
Division: __________________

When there are multiple answers, please *circle* the one best suited to your case.

1. How many years of experience do you have in cost estimating?
   a) less than 3 years b) 3-5 years c) 5-10 years d) 10-20 years e) more than 20 years

2. Which of the following category does your company belong to?
   a) Product-based b) Service-oriented c) Both

3. What is the scale of product and engineering services offered in your company by revenue? (Please circle it on the scale)

   Pure Product Non-Product

   100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 0%

   Pure Engineering Services Non- Engineering Services

   100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 0%

4. Do you explicitly cost estimate product and engineering services differently?
   a) Yes b) No
   If the answer is YES, please indicate the differences.

   ____
   ____
   ____
   ____
   ____

5. Does your company offer engineering services via
   a) Through life support b) Service contracts c) Leasing
   d) Others (please indicate) ____________________________________

6. Do you do costing for engineering services using product costing tools?
   a) Yes b) No
   If the answer is YES, what are the challenges you experience or modifications you have to make as a result of using these tools?

   ____
   ____
   ____

   If the answer is NO, what are the other costing tools you use for costing engineering services?

   ____
   ____
   ____

7. Definition:

Co-creation of value: involves customers in the process of designing and delivering what customers want (e.g. if a customer wants to hire a car for a holiday, a car provider has to find out things such as when they need it, which car they prefer, how long they need it for. The value which provides a satisfactory leasing service is created through the interaction and co-operation between the service provider and the customer.)

Does your company involve customers as part of the co-creation of value?

a) Yes b) No

If the answer is YES, how do you involve your customers in designing the engineering services?

____

____

____

Do you measure your customers' input to the process?

a) Yes b) No

If the answer is YES, how do you measure their input and using which metric (quality, time etc.)? If NO, then why don't you do this and what are the challenges?

____

____

____

____

p) The table shows a spectrum of cost estimation techniques. Please fill in the table as required.

a. Intuitive Techniques: based on using past experience, including experts' knowledge
b. Analogical Techniques: based on using historical cost data for products with known cost
c. Parametric Techniques: based on statistical methodologies to express unit cost. Often used in top-down approaches
d. Analytical Techniques: based on mathematical equations to separate a product into elementary units, operations, and activities during the production cycle and express the cost as a summation of all these components
e. Others, please fill in the table

Cost Estimation Techniques	Please tick the ones that you use for cost estimation	Please name the cost estimation technique (e.g. Work breakdown Structure)	Please name the modelling tool/software you use (e.g. SEER)	Please explain why you use this technique	Please give a typical example of when you use this technique (e.g. for service contract)	Please point out the possible problems which may occur when using this technique (leave blank if it is without any problems)
a. Intuitive Techniques						
b. Analogical Techniques						
c. Parametric Techniques						
d. Analytical Techniques						
e. Others						

9. Definitions:

I) Product Cost Model: the mathematical and logical methodologies used to predicatively calculate what a physical product costs (in terms of time and money) to manufacture and deliver to the customer (e.g. the cost model for producing a Ferrari F1)

II) Engineering Services Cost Model: the mathematical and logical methodologies used to predicatively calculate what engineering services costs (in terms of time and money) to design and deliver to the customer (e.g. the cost model for keeping an aeroplane flying)

Which cost modeling types have you had experience of using?

a) Product Cost Model b) Engineering Services Cost Model c) Both Product and Engineering Services Cost Models

If you selected c) as the answer, please indicate any similarities and differences between the product cost estimate model and engineering services cost estimate model?

____

____

____

____

____

q) Forecasting is commonly used in cost modelling. Please indicate all the type of things you forecast and the basis or process for generating your forecast.

____

____

____

____

____

11. Definition:

Engineering services Costs: Costs occur when the platform/product is running, e.g. cost factors of running an aircraft may include on-aircraft maintenance of the fleet, spares support, technical support and training.

Does your company use cost modelling for estimating engineering services costs?

a) Yes b) No

If the answer is YES, what is the current model type being implemented?

____

If the answer is YES, what would you suggest to improve the current engineering services cost estimating model?

____

____

____

____

____

12. Definition:

Service blueprint: a graphical tool used to describe how the service process works, how service provider and customers interact, and what customers would receive from the service.

If you are a service-based company, do you use service blueprint to design the engineering services process?

11. Yes b) No

If the answer is NO, please list the other methods (e.g. value stream mapping).

Do you modify your method to fit engineering services?

a) Yes b) No

If the answer is YES, please explain how you modify it.

Thank you for participating in this survey. Your responses will assist with our research into improving in-service cost modelling. If you would like to discuss our research further, please complete your details below.

Your name:
Your e-mail address:
Your contact number:

Appendix B Questionnaire about Cost Estimation with XX Maintenance Staff

Survey Target: maintenance staff

N/B: A copy of the Chinese version of this questionnaire was used for respondents.
Machine parts were anonymous in Question 7.

Company Name: Industrial Case Study Company

Division: After-sales services department

For the following questions, please fill them in based on your own experience rather than from the database.
When there are multiple answers, please *tick* as requested.

1. How many maintenance staff are there in the after-sales department?

2. What is your main role within the department?

3. How long have you been working in this company?

4. How many times a month is you sent to customers' companies to undertake maintenance services?

5. Please fill in the table as requested.

Maintenance Type	Please write down the proportion of each maintenance service you have provided to customers (CM+PM+CBM=100%)	Please rank the maintenance service with 1 being most important
Corrective Maintenance (CM)		
Preventative Maintenance (PM)		
Condition Based Maintenance (CBM)		

Definitions:
CM: Maintenance and repair actions are applied only if the system or the component enters the failing state
PM: a scheduled maintenance plan conducted at predefined time intervals or system usages
CBM: a predictive maintenance triggered by some predefined value(s) or metrics indicating the deteriorated system "health" condition

6. At present, do you think these three types of maintenance service (CM, PM and CBM) have been provided at the appropriated amount to customers?
   a) Yes b) No

   If the answer is b), which type of maintenance service should be provided more of? And why?

   ____
   ____
   ____

7. Please fill in the following tables as requested. Please select only the top three with 1 being most important.

Common Machine Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Rank the top 3 most likely breakdown sections															

Write down the section number of three most likely breakdown parts you selected in previous table	Write down 3 most common failure parts, such as, bearing etc for each of the selected parts.	For the failure parts that you just wrote down, are they repairable (write down ✓) or non-reparable (write down ×)?	For the failure parts that you just wrote down, how often do they need to repair or replace (e.g. X times per year)?	For the failure parts that you just wrote down, how many staff are required to maintain or replace the failure parts?	For the failure parts that you just wrote down, how long does it take to maintain or replace these failure parts?	For the failure parts that you just wrote down, what are the main reasons for causing they failed or broke?

8. If customers requested for a visiting service, in what circumstances were you agreed to provide such services? (Only one answer could be selected)
    a. Only when the technical problem could not be solved over the phone
    b. Whenever the customer requested
    c. You have a good relationship with the customer
    d. The customer is close by

9. If you provided phone services to customers, how long does it normally take you to solve a technical problem?

10. If you provided phone service to customers, what were the general issues customers needed support with?

11. Based on your experience, at present what percentage of technical issues has been solved over phone rather than visiting customers? Ideally, what this percentage should be? (Please circle it on the scale)

At present:

Over phone =100% Visit customers=100%

- 100:0 90:10 80:20 70:30 60:40 50:50 40:60 30:70 20:80 10:90

Ideally:

Over phone =100% Visit customers=100%

- 100:0 90:10 80:20 70:30 60:40 50:50 40:60 30:70 20:80 10:90 0:100

12. Based on your experience, do you think some issues solved in the customer's factory could be solved over phone?
    a) Yes b) No

    If the answer is Yes, please write down what kind of issues can be solved over phone instead of going to site?

    ____

    ____

    ____

    ____

    ____

13. When the new machine is delivered to the customer's company, have you been there to provide training services?
    a. Yes with service charge b) Yes without service charge B) No

    If tick a) or b), please write down the training length and training contents.
    If tick a), please also write down the training service charge that you offered.

    ____

    ____

    ____

    ____

    ____

14. Please fill in the table as requested. If you think any of these services should not be offered, please write down "*not apply*" in the corresponding box.

If you provide an after-sales service contract					
how many times of customer requested repair visiting services would you offer per year ?	how many times of regular visit for routine checking would you offer per year?	how many times of customer requested repair phone services would you offer per year ?	how many times of phone services for routine checking would you offer per year?	how many times of training services would you offer per year ?	Write down any other services if you think it is important to have

Based on the figures you write down, please write down how much you think this service package should be charged per year to cover the associated expense?

____

Thank you for participating in this survey. Your responses will assist with our research into improving in-service cost modelling. If you would like to discuss our research further, please complete your details below.

Your name:

Your e-mail address:

Your contact number:

Appendix C Questionnaire about Model Verification and Validation

Survey Target: 8 maintenance staff
N/B: A copy of the Chinese version of this questionnaire was prepared for respondents.

Company Name: Industrial Case Study Company

Division:
Your role:

Experiment process:
a) I will explain the process/logic of the model to the experts <u>without</u> presenting the model.

To assist the cost estimation of a service, an approach for estimating the cost of engineering services is presented.

1. Select an industrial case study (Chapter 6)
   - Reasons for selecting the case study company
   - Research the background of the case study company
   - Collect and analyse historical cost data from the case study company

2. Create an engineering services cost model (Chapter 7)
   - Identify the scope and process of engineering services cost modelling
   - Identify performance factors and CERs of the engineering services cost model
   - Apply the bathtub failure model and stage within the bathtub using the historical data

3. Validate the engineering services cost model (Chapter 8)
   - Validate the concept and principles of the engineering services cost model using experts opinions
   - Validate the engineering services cost model by splitting the machine data into mechanical and electrical data

4. Test service scenarios and propose service solutions with associated costing (Chapter 9)
   - Propose how to price an engineering service contract based on 1, 3, 5, 7, 9, 11, 13 and 15 years in operation
   - Propose how to allocate on-site staff based on the number of machines in operation

An approach for estimating the cost for engineering services using parametrics and the bathtub failure model

b) Then the experts are asked to complete the following questionnaires.

1. If the model satisfies with the following statements, please "✓" in the box; If the model does not satisfies with the following statements, please "x" in the box and presents your reasons and ways for improvements.

Cost Model	"✓" or "x"	Reasons	Recommendations for improvements
1) The process of the cost model seems correct.			
2) The logic of the cost model seems correct.			
3) The cost estimating relationships seems correct.			
4) The specification of the cost model meets company's targets.			
5) The model reflects real-life.			

2. Overall, what do you think of the cost model? (Please circle it on the scale)

Poor =0% Excellent =100%

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

3. Overall, how do you think the model could be improved?

Thank you for participating in this survey. Your responses will assist with our research into improving in-service cost modelling. If you would like to discuss our research further, please complete your details below.
Your name:
Your e-mail address:
Your contact number:

Appendix D Validation and Extension Scenario

Survey Target: 4 maintenance staff

Company Name: XX Company

N/B: A copy of the Chinese version of this scenario was prepared for respondents.

Validation and Extension Scenario:

We wish to sell 100 XX machines from the same production line. Each machine was sold to a different customer in Mainland China. These customers are requesting that we enter into an engineering service contract with them. The options are different contract lengths--one, three, five, seven, nine, eleven, thirteen and fifteen years. What are the machine failure rates for 100 machines per year at different contract lengths?

Please estimate the costs for providing such a service based on your experience.

T=Contract length (years)	What is the machine failure rate for 100 machines per year?															Explain how you obtain this value
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	
1		-	-	-	-	-	-	-	-	-	-	-	-	-	-	
3				-	-	-	-	-	-	-	-	-	-	-	-	
5						-	-	-	-	-	-	-	-	-	-	
7								-	-	-	-	-	-	-	-	
9										-	-	-	-	-	-	
11												-	-	-	-	
13														-	-	
15																

Appendix E Scenario 1

Survey Target: 4 maintenance staff

Company Name: XX Company

N/B: A copy of the Chinese version of this scenario was prepared for respondents.

Scenario 1:

We wish to sell 100 XX machines from the same production line. 100 machines were sold to the same customer in Mainland China. The customer is requesting that we enter into an engineering service contract with them. The options are different contract lengths--one, three, five, seven, nine, eleven, thirteen and fifteen years. What are the machine failure rates for 100 machines per year at different contract lengths?